EXAMINING THE EFFECTS OF SPACE FLIGHT ON THE MUSCLES

THE EFFECT OF SPACE FLIGHT ON THE MUSCULAR SYSTEM

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INTRODUCTION

Pump iron for a month and, presto, your muscles get stronger. Take to your La-Z-Boy chair for a month and your muscles go soft (Figure 1). Everyone knows this happens, but why does it happen? Why should you have to work to keep your muscles in shape? Why can't you relax and take a pill that duplicates two hours at the gym? Or wouldn't it be nice to be able to just swallow a can full of spinach and physically transform ourselves, as Popeye the sailor man is able to do? Unfortunately, we all know it's not that easy. In this chapter we are going to examine how our muscles work and this will lead us to understand what we must do to "feed" our muscles so that they do not atrophy, or get soft and waste away. We will start with a description of the structure and mechanical action of muscles. We will then look at the chemical activities that take place in the muscles to assure that they receive the appropriate levels of energy to keep us moving. Finally, we will learn about an important space study that was carried out to see how and why the muscles of astronauts can change their very character as they adapt to the new environment of space where the natural gravitational pull is absent. Let's first examine how the muscles behave on Earth.

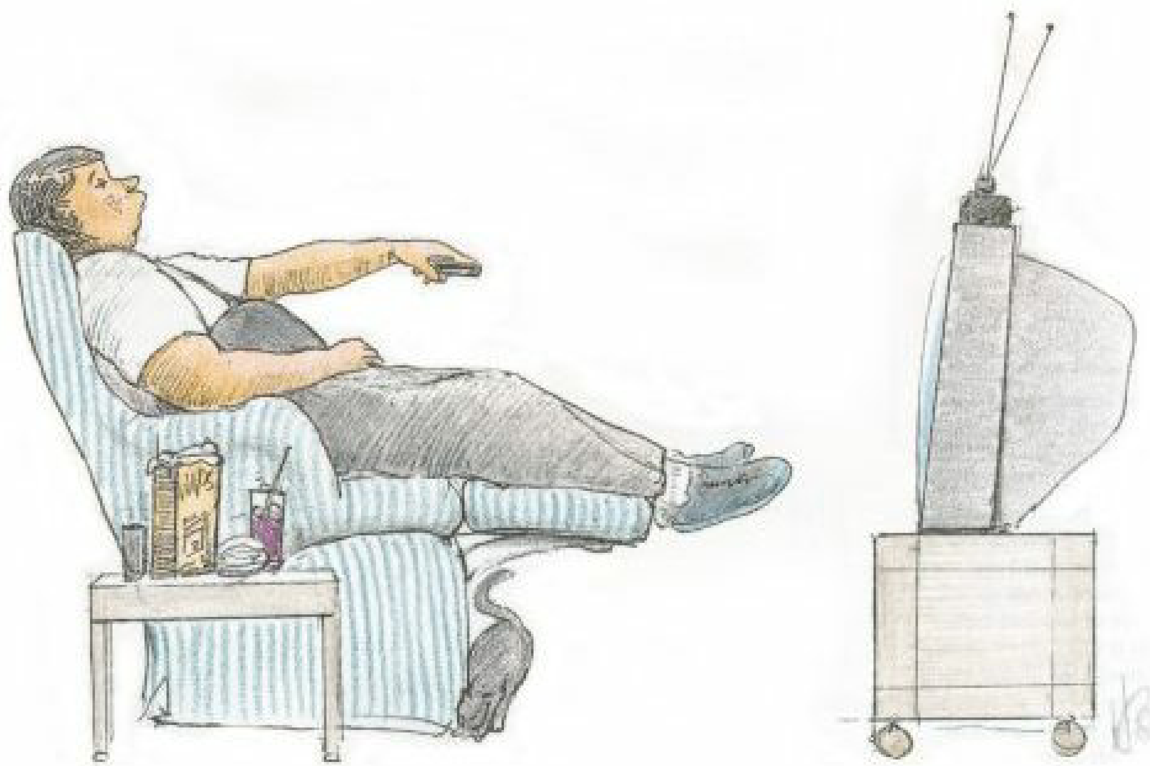


Figure 1. Use of the television remote control may build muscles in the index finger, but the rest of your body requires movement and exercise.

EARTH PHYSIOLOGY

Humans have about 700 muscles in their bodies; these muscles make up about 50% of body weight. The many muscles in our bodies operate as cables (similar to elevator cables) that pull on bones to make motion possible. Their sole function is **contraction**, that is, they all work by shortening. By working in pairs, however - one muscle contracting to pull a bone forward, the other to pull it back - the muscular system is capable of an immense variety of movements, from wagging the tongue in everyday conversation to running a race. Most of these contractions are controlled and coordinated by the brain. But others occur without the brain even having a clue that something is happening! So interrelated are muscles that one contraction usually involves many others. In fact, the track athlete, exercising many muscles, even grins (or possibly grimaces) as he or she runs!

There are three types of muscles in our bodies - **skeletal muscle, cardiac (heart) muscle, and smooth muscle**. Although we will be most interested in skeletal muscle in this chapter, let's briefly review the other two so that we can understand the similarities and differences in the muscle types. Let's begin with the differences.

The muscle types differ not only in their function, but also in their appearance (Figure 2). Skeletal muscle has a striped appearance (also called **striated**). Cardiac muscle is also striated, but the stripes are much less organized and contain branches to allow for extremely rapid communication, and smooth muscle is not striped at all, but instead is composed of obvious, distinct cells with very dark nuclei. The appearance and make up of the different muscle cells are indicative of their function, as we will see. First of all, the heart itself is a muscle - it is called the **cardiac muscle**. In fact, the heart is the muscle in the body with the greatest endurance. It beats about 100,000 times per day without our conscious control; that is, cardiac muscle contractions are **involuntary**.

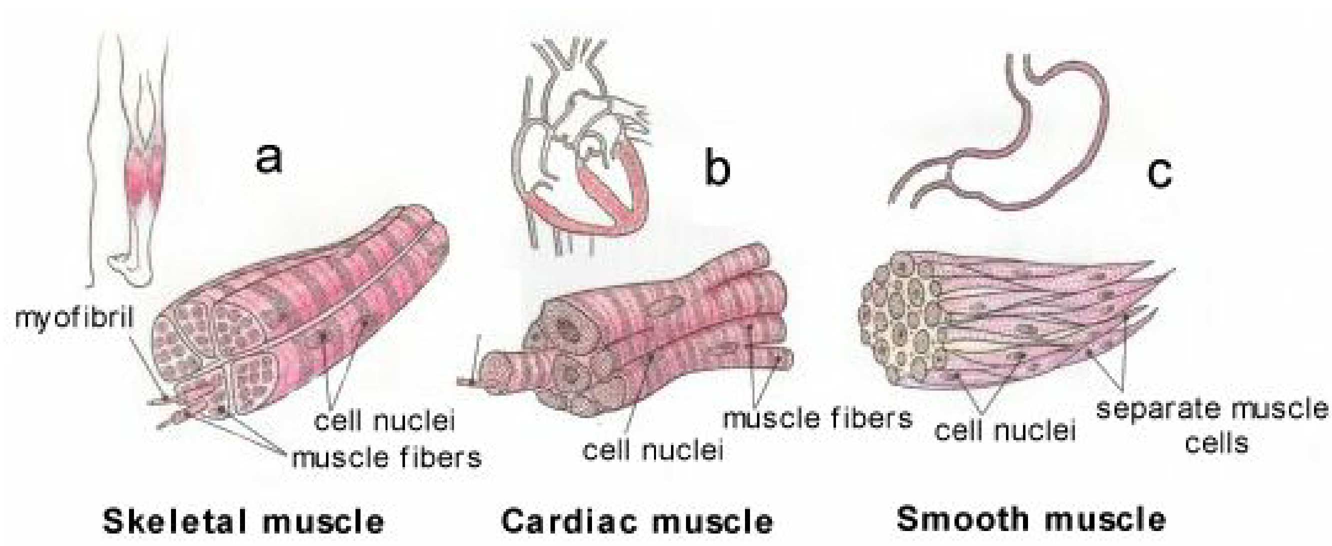
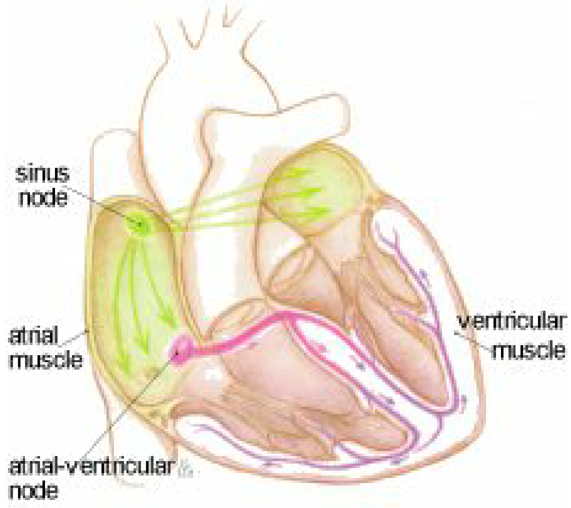


Figure 2. There are three types of muscles in the body. (a) Skeletal muscle has a very organized striated appearance. (b) Cardiac muscle also has a striated appearance but the cells are much less organized. (c) Smooth muscle is not striated but consists of distince cells, each with a very dark and obvious nucleus. There are actually two types of smooth muscle cells, multi-unit (the cells of which can operate independently) and visceral (where the cells operate together as a unit).

The heart is composed of three major types of cardiac muscle: atrial muscle, ventricular muscle, and neuromuscular muscle fibers that provide the transmission system for rapid conduction of the cardiac excitatory signal throughout the heart (Figure 3). In simple terms, this means that these specialized cardiac muscle fibers keep all of the heart muscles working together in rhythm. Of the three, the ventricular muscle is by far the thickest and most powerful. This makes sense since the ventricles are responsible for providing the powerful thrust to propel blood out of the heart and around the body.

Figure 3. Cardiac muscle cells (fibers).



Although there are different regions and thicknesses of muscle in the heart, the entire heart muscle works as a single unit. The specialized structure of the cardiac muscle cells allows for this continuous, rapid, and unified action among all the cardiac cells. The heart must work as if it were one muscle because of the importance of maintaining a constant heart rhythm to keep the blood flow as constant and stable as possible. Think about a cheerleading squad at one of your school sporting events or even a chorus or band ensemble performing at a school assembly. In each case, it is important for the entire group to perform with the same rhythm or else the quality of the performance is decreased. The same goes for the rhythm of the heart (although, unlike a cheerleading, chorus, or band performance, abnormalities in heart rhythm can be dangerous to your health). If the various heart muscle contractions do not occur in rhythm with one another, the quality of the life of an individual can decrease, if not cease altogether In fact, certain dangerous disease states do exist that are characterized by abnormal heart rhythms.

Smooth muscle is another **involuntary** muscle group. There are two types of smooth muscle: **multi-unit smooth muscle** and **visceral smooth muscle**. Multi-unit smooth muscle is composed of cells that can operate independently of one another. Visceral smooth muscle, on the other hand (often called single-unit smooth muscle), is composed of cells that, collectively, function together as a single unit. Some examples of multi-unit smooth muscle found in the body are the muscle in the iris of the eye (which causes the iris to either dilate or constrict), the muscles that cause erection of the hairs when stimulated by the nervous system (for instance, when you are so scared that your hair stands on end), and the muscle of the larger blood vessels (that help to either dilate or constrict certain sections of the blood vessels).

Visceral smooth muscle is found in the walls of most of the hollow organs of the body, especially in the walls of the gut, the intestines, the ureters, the bladder, and the uterus. As you can well imagine, then, each smooth muscle group has a very specialized function distinct from the others: in the uterus it must work to help a woman deliver her baby; in the bladder it must work to help push urine into the urethra, which also contains smooth muscle, to squeeze urine (and sperm in the male) out of the body. Because of smooth muscle, these functions do not depend on gravity to aid in the extraction of their respective biological "contents." The best example to illustrate the nature of visceral smooth muscle is to consider the digestive system including the gut and the intestines.

Figure 4. Circular and longitudinal smooth muscle layers.

Because of the smooth muscle, food requires no help from gravity to make its way through the esophagus, out of the gut, and through the coiled intestinal pathway (in fact, an astronaut's digestive system works very well in a microgravity environment). The power to move the food through the digestive tract is furnished by muscles that stretch the full length of the tract. They form two layers, one running along the tract and the other encircling it in concentric rings. By setting up a churning motion, and by a series of progressive contractions known as **peristaltic waves**, these twin sets of muscles force food all the way from the esophagus in the throat to the rectum, much as if toothpaste were being squeezed along its tube by some built-in power in the tube walls (Figure 4). The muscles of the esophagus squeeze and relax in concert; these muscles mix the food and propel it along. These peristaltic waves are so powerful that they will move swallowed food even if you stand on your head! The stomach is also lined with smooth muscle. It hangs folded when empty but it can stretch to accommodate more than a quart of food before moving it slowly into the intestines. We have all felt (and even heard) the smooth muscle contractions, or peristaltic waves, coming from our intestines. This occurs as the food is being broken down and digested and just before our bodies signal us to eliminate the "digested food!" The final exit for this digested food is also lined with one of the smooth muscle groups known as a sphincter. So, even though you may have never known the physiological basis for your elimination of solids, each and everyone of us has many years of experience dealing with the practical usage of these muscles! Well, let's change the subject and get on to the main topic for this chapter - skeletal muscle.

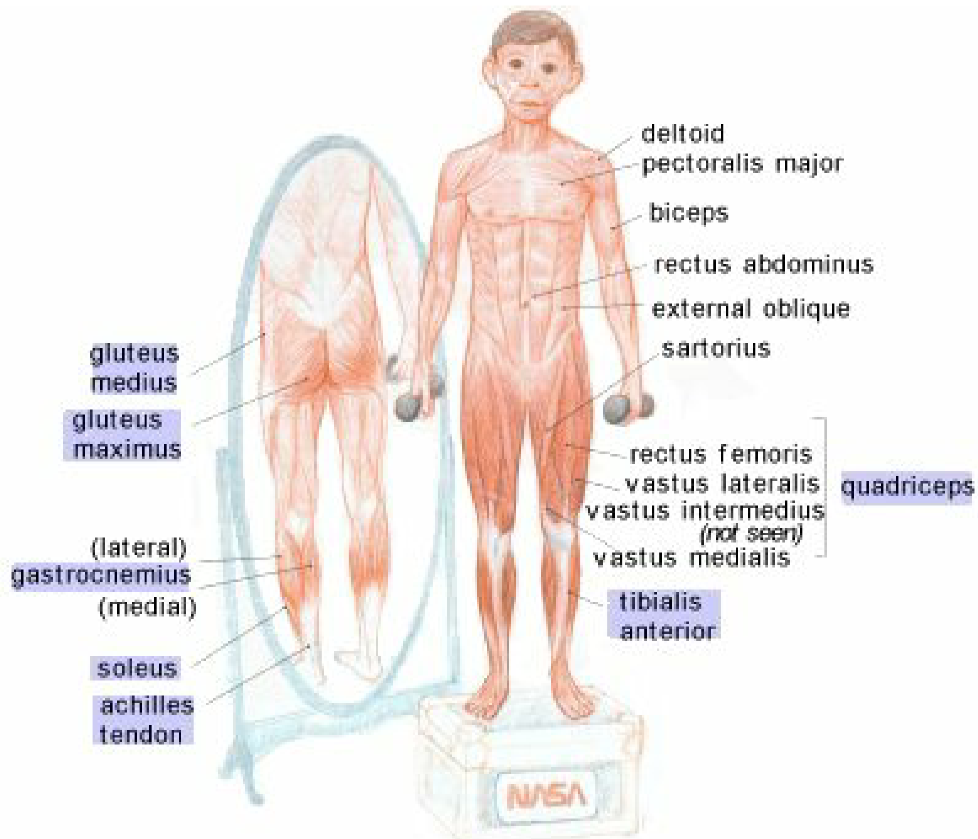
Skeletal Muscle

Like the bones, the skeletal muscles range in size and shape to suit the particular functions they perform. As you are reading this, raise your eyebrows. Now smile! Now frown! Now wiggle your tongue (not at anybody, please)! Now close your eyelids (but don't go to sleep, we still have work to do)! As you are performing these facial movements, you are using many different muscles, some of which are less than an inch long. Even with their shortness, the muscles of the eyelid are the fastest contracting muscles in the body. And in order to smile, you are using 14 different face muscles!

Of course, we can't cover all 700 or so muscles in the body, but we will review some of the more familiar ones. Let's look at some of the larger muscles in our bodies. Take a deep breath. You are experiencing the effect of movement of the **diaphragm**, which is the dome-shaped muscle located at the floor of the chest. It is the main muscle involved in breathing, and is also involved in coughing, sneezing, laughing and sighing. The diaphragm must constantly work whether we are on Earth or in space since breathing is essential to survival. That is, the **function of the diaphragm does not change if gravity is removed**.

Now let's look at some of the larger muscles that change their function when gravity is removed (Figure 5).

Figure 5. The major skeletal muscle groups of the body. The anti-gravity muscles, in particular, owe their importance and strength to the presence of gravity.



These are the muscles that we use for **locomotion -** the physical movement of our body. Although these muscles are not considered essential for survival in the same way that the muscles of the heart and some other organs are, they are extremely important for enabling us to carry out our day-to-day activities. All of these muscles have "grown up" and have been trained to work in the presence of gravity. For instance, the bulging triangular **deltoids** of the shoulders raise the arms. The **biceps** and **triceps** of the upper arms bend and unbend the elbows. The broad **pectoralis** major muscles, those rippling signs of the he-man, move the arms across the chest. **Without gravity, their jobs would become easier.**

There are other muscles, however, that function almost entirely **because of gravity**. That is, their function is to create movement that opposes the gravitational pull of the Earth. These are broadly referred to as **anti-gravity muscles** but are also known as **postural muscles**. They are located primarily from the lower lumbar spinal area down to the feet. For instance, the massive **gluteal** muscles of the buttocks (the largest combined muscle group in the body) help us maintain posture (to stand up) and to stabilize our hips (for walking and running). The longest muscle in the body is in the thigh; it is known as the **sartorius muscle**. The sartorius muscle and the four bundles of muscles on each side of it called the **quadriceps** not only move the legs but also help us maintain our balance. The **soleus** and the **gastrocnemius** muscles in the calf work together with the **tendocalcaneus** (or **Achilles tendon**) in the ankle to lift the body onto the heel and feet. And, of course, the feet have a multitude of muscles which help us to mobilize ourselves while in an upright position. Although we've mentioned only a few of the anti-gravity muscles, the main point to make here is that these muscles have been trained to do their work only in the presence of gravity. To a certain degree, these muscles owe their importance and strength to gravity!

Whether large or small, the skeletal muscles can perform with extraordinary speed and power. Such qualities can be literally of life-or-death importance here on Earth, enabling the body to move in response to sudden and drastic changes in the external environment. Skeletal muscle can get into action within a **few hundredths of a second** (not a few hundred seconds, a few hundredths of a second), exert an enormous concentrated pull on the bone to which it is attached and, when necessary, support 1000 times its own weight. But, as you are about to learn, different muscle types are equipped to handle different levels of activity.

As mentioned previously, all muscle (including skeletal, visceral, and cardiac) moves by **contracting itself**. This unique characteristic distinguishes it from any other body tissue. In the case of skeletal muscle, the individual cells (which are also called **fibers**), ordinarily long and thin, become shorter and fatter under stimulus and take on their tremendous pulling power. Once the stimulus has passed, the muscle relaxes, settling back into its original shape. There are two primary kinds of fibers. Marathon runners typically develop a type of **slow-moving but high-stamina fiber**, which is named **Type I** or, **"slow twitch."** For instance, the soleus muscle in the calf has a high percentage of slow twitch muscle fibers and therefore is said to be the muscle that is used to a greater extent for prolonged lower leg muscle activity.

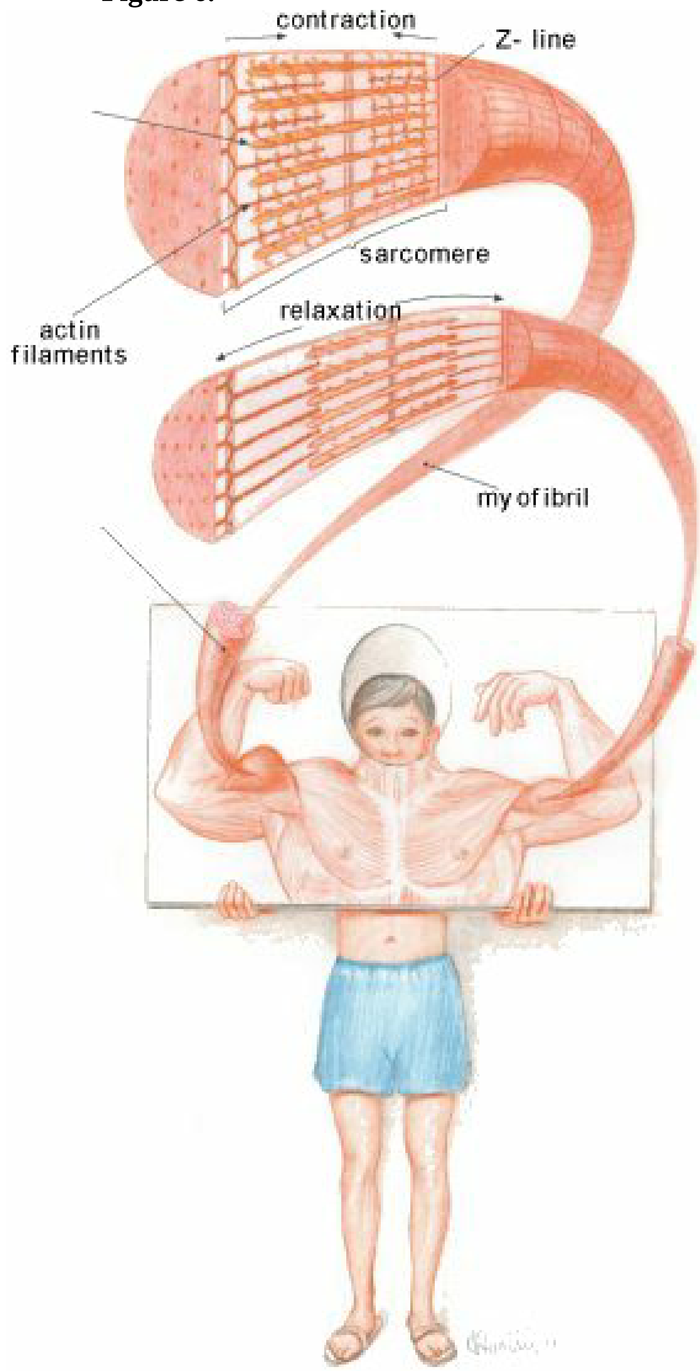
On the other hand, sprinters and power lifters typically develop a type of **high-speed, high-output fiber** called **Type II** or **"fast twitch."** For instance, the gastrocnemius muscle in the calf has a higher percentage of fast twitch fibers, giving it the capability of very forceful and rapid contraction of the type used in jumping or for quick, powerful "bursts" of movement. The average person has about half of one type and half of the other throughout the body. We will discuss this later. The important point here is that all muscle cells, fast twitch or slow twitch, operate by contracting (shortening) the microscopic filaments that each muscle fiber contains. Let's examine how this process works.

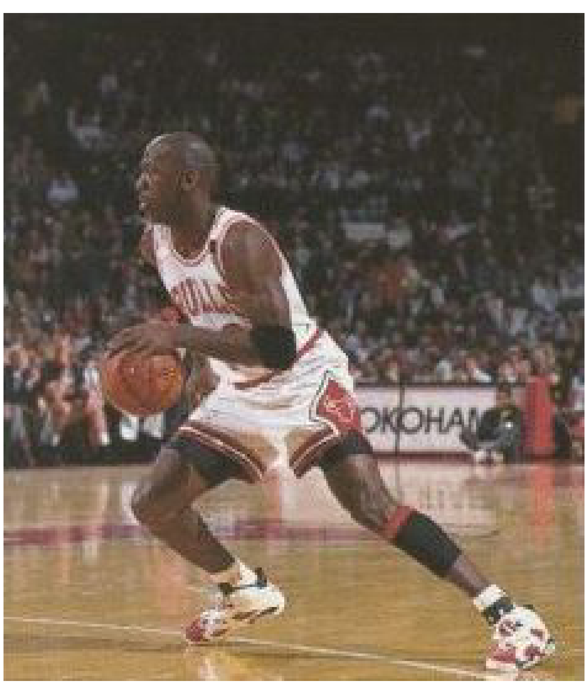
Muscle Filaments - The Engines of the Muscle

You know what your muscles look like if you have ever examined a beefsteak. They are not a solid mass but, instead, consist of a dense package of thin, fleshy layers. As mentioned previously, the muscles are composed of **fibers**, which are the cylindrical muscle cells (Figure 6). Each fiber is made up of smaller units called **myofibrils** (myo = refers to muscles, fibril = smaller fibers). Each myofibril consists of many **filaments - the engines of the muscle**. If you were to view a muscle through a very high-powered microscope you could actually see that there are two kinds of filaments - thick and thin. The thick filaments are made of the protein **myosin**, and the thin ones are made of the protein **actin**. Together the actin and myosin provide all of the muscle's movement and force as they slide together (during contraction) and apart (during relaxation).

The actin filament is anchored to vertical bands called **Z lines**. The part of a fibril from one Z line to the next is called a **sarcomere**. The myosin filament is located between each actin filament in the sarcomere and together they operate like a sliding hatch (Figure 6). When the muscle fiber is relaxed, the hatch lies "open" and the sarcomere is at its greatest combined length. But when the myosin receives the power command, it pulls the hatch "closed." That shortens the combined length of the sarcomere and provides each filament's tiny share of the muscle contractions.

Figure 6.





The filament's force is **all or nothing**. When called upon, it always applies the same amount of force at the same speed. Equivalent types of filaments are identical in Michael Jordan and Mother Teresa (Figure 7)! But there the resemblance ends. The filaments are bundled into muscle fibers about the size and shape of a thin hair a few millimeters to a few centimeters long. Michael Jordan's fibers, however, are perhaps twice as thick as Mother Teresa's, because physical conditioning and the male hormone testosterone have added more filaments to each fiber for additional strength. About 100 to 500 fibers are wrapped together like a package of spaghetti to form a "motor unit," the smallest muscle unit that can be controlled individually. When Jordan shoots a basketball, his brain calculates just how many and which motor units are required in various muscles and activates only those. If the calculation is correct, Jordan scores!

Your genes may not have endowed you with a professional athlete's muscle make-up, but you make similar calculations every time you lift a box or open a door. The brain's orders reach the muscles because a nerve from each motor unit is plugged into the spinal cord like a telephone plugged into a wall socket. But unlike the telephone, if you unplug the muscle, it still works. The reason is that muscles take orders from more than the brain. Some nerves from motor units go to the spinal cord and up to the brain, but others loop back and connect to other motor units, to the skin and to other body tissues. Through these loop back circuits, muscles and skin can communicate among themselves, allowing muscles to react faster than the brain can. The classic example is touching a hot surface. Your skin sounds the alarm, and the muscles pull your hand away before the news even reaches your brain! In either case, muscles require nutrients in order to supply the energy for muscular contractions.

A combination of mechanical and chemical mechanisms play a part in providing the nutrient and energy supply for these muscular activities. Chemical changes occur in the muscle, which causes a conversion of chemical into mechanical energy. This produces the actual movement of muscle contraction. In order to sustain the movement for any length of time, however, a supply of nutrients is required so that sufficient energy can be maintained in the muscle as it continues to work. Let's examine the chemical reactions that create the energy for the muscles to move our bodies.

Muscle Energetics

The best way to define energy is to describe what it does. **Energy** is the ability to do work or cause motion. Common forms of energy in our world include heat, light, sound, electrical energy, mechanical energy, and chemical energy. Most metabolic processes in the body use **chemical energy**, which is held in the bonds between the atoms of molecules and is released when these bonds are broken. The muscles are no different. When muscles work, they require energy so that they can contract. The unique feature about muscular contraction is that the chemical energy is transformed into mechanical energy - movement. Although extended muscle activity depends on the provision of important nutrients such as carbohydrates, fats and even protein, the basic source of chemical energy for muscle contraction is **adenosine triphosphate** or **ATP**, which has the following basic chemical formula:

$$\textbf{Adenosine - } PO_4 \sim PO_3 \sim PO_3$$

The bonds attaching the last two phosphate radicals to the molecule, designated by the symbol ~, are so-called high energy phosphate bonds. When these bonds are broken (and new bonds are formed), a large amount of chemical energy is released. In fact, each of these bonds stores about 11,000 calories of energy (per mole of ATP) in the body. (A **mole** is equivalent to Avagadro's number - 6.02 x 10 - of molecules.) Therefore, when one phosphate radical is removed from one mole (6.02 x10 molucules), 11,000 calories of energy that can be used to energize the muscle contraction process are released. Then, when the second phosphate radical is removed, still another 11,000 calories become available. Removal of the first phosphate converts the ATP into **adenosine diphosphate** or **ADP** and removal of the second converts this ADP into **adenosine monophosphate** or **AMP**.

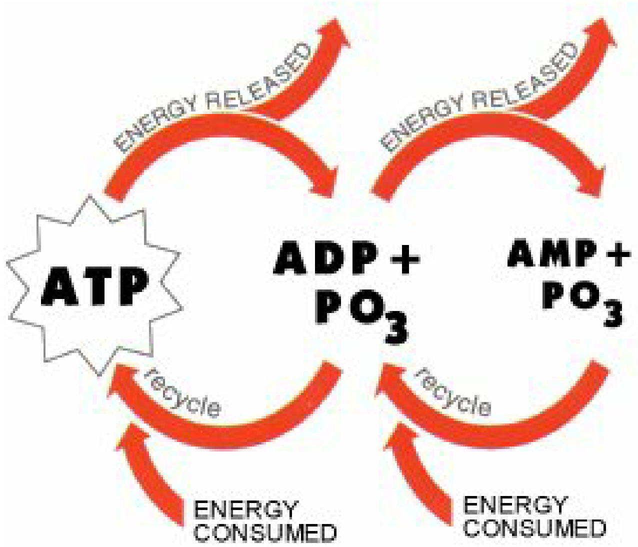


Figure 8.

Figure 8 shows the breakdown of ATP first to ADP and then to AMP, with the release of energy to the muscle for contraction. **The energy, then, for muscle contractions is actually produced by the breaking apart of ATP into ADP and then again into AMP**. But in order to have an adequate supply of ATP, the AMP must be **recycled** back into ADP and then it must be **recycled** back into ATP. To do so involves adding a phosphate molecule to each step.

The left-hand side of Figure 9 shows the three different metabolic mechanisms that are responsible for recycling AMP and ADP back into ATP in order to provide a continuous supply of ATP in the muscle fibers. **Why** do we have three different metabolic systems in our bodies to produce the ATP? Well, each one serves a different metabolic need that we may have depending on the level of movement or activity that we participate in. The longer and more intense the muscular activity, the greater is our need to supply ATP more rapidly to those muscles. Let's examine how our bodies provide this important fuel.

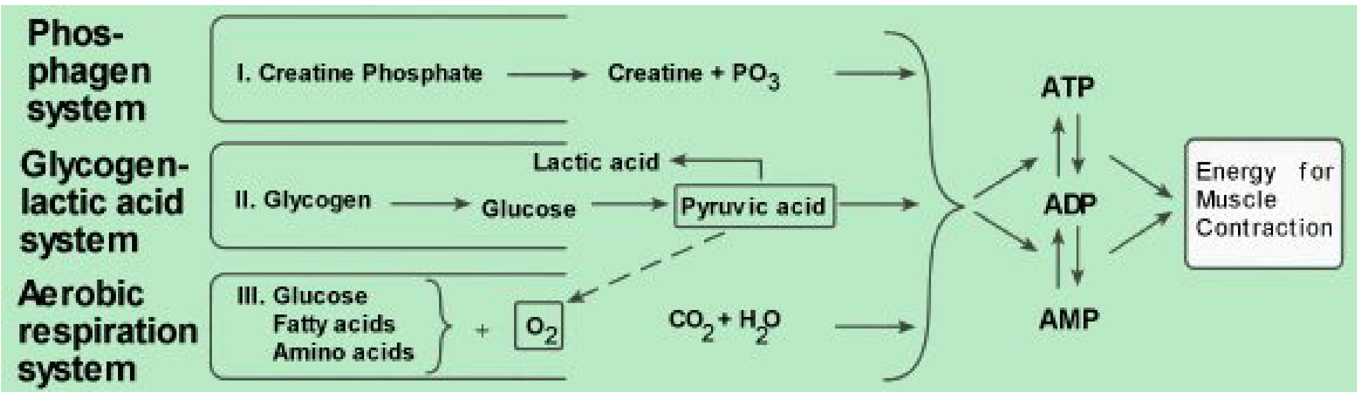


Figure 9. The three important metabolic systems that supply energy for muscle contraction: (1) The phosphagen energy system, (2) the glycogen-lactic acid system, and (3) the aerobic system.

Unfortunately, the amount of ATP that is present in the muscle cells, even in the well-trained athlete, is only sufficient to sustain maximal muscle power for 5 or 6 seconds, maybe enough for a 50-meter dash. Therefore, except for a few seconds at a time, it is essential that **new ATP** be formed continuously, particularly during the performance of athletic events. However, different kinds of athletic events require different amounts of energy. Some athletic events such as a 100-meter dash, weight lifting or certain football plays require a quick "burst" of energy. In this case, the amount of ATP present in the muscle cells is not enough to sustain the muscle power that is needed. Therefore, the body must rely on the **phosphagen system**, which utilizes a substance called **creatine phosphate** (which also contains a high energy phosphate bond) to recycle ADP back into ATP to provide fuel for our muscles (Figure 9). This is accomplished when the high energy phosphate bond in creatine phosphate breaks down and releases phosphate and energy. The phosphate molecule and the energy then combine with ADP to form ATP. In simple terms, the reaction goes like this:

Creatine ~ PO_4 ♦ Creatine + PO_4 + Energy

PO_4 + Energy + ADP ♦ ATP

Therefore, ATP can be produced using the phosphagen system so that our bodies can sustain about 10 to 15 more seconds of muscle activity. This is all fine for short, quick, intense bursts of energy. But the **significant energy producing mechanisms in the body -** those that allow us to use our muscles for longer and more intense periods **-** require the breakdown of the sugars in our bodies **- glucose**. The complete breakdown of glucose, which is needed to supply ATP during heavy muscular activity, occurs in two steps. The first stage of glucose utilization is called **anaerobic** because oxygen **is not used**. The second step, when physical activity becomes even more vigorous, is called **aerobic respiration** (aerobic = occurring in the presence of oxygen) because oxygen **is used** to produce even more energy. Let's discuss each step individually.

Certain athletic events, such as longer track events (200- or 400-meter dash events and longer), basketball, tennis or soccer require **extra ATP** to fuel the muscles. During these times of heavy physical activity, glucose molecules come to the rescue. The extra ATP that is needed by the muscles is provided by a system that breaks down glucose **in the absence of oxygen**. This system **-** the **glycogen-lactic acid system -** is the anaerobic step of glucose breakdown (Figure 9). In this step, each glucose molecule is split into two **pyruvic acid** molecules, and energy is released to form several ATP molecules providing about 30 to 40 seconds of maximal muscle activity in addition to the 10 to 15 seconds provided by the phosphagen system. The pyruvic acid will then partly break down further to produce lactic acid. If the **lactic acid** is allowed to accumulate in the muscle, you will experience muscle fatigue (often characterized by pain such as cramps).

The **aerobic system** in the body is utilized for those sports that require an extensive expenditure of energy, such as a marathon race or cross-country skiing. Lots of ATP must be provided to your muscles in order to sustain the muscle power that you need to perform such events without excessive production of lactic acid. Therefore, in the presence of oxygen, pyruvic acid breaks down into carbon dioxide (CO_2), water, and energy by way of a very complex series of reactions known as the **citric acid cycle**, providing essentially unlimited time (as long as nutrients in the body last) to continue muscle utilization (Figure 9). As you know by now, oxygen travels around the body in the blood vessels by attaching to the hemoglobin of the red blood cells. However, in the muscles, some oxygen can be stored in a special chemical substance found within the muscle fibers called **myoglobin**(remember, myo = refers to muscle). The myoglobin is similar to hemoglobin in its oxygen-binding capability but it can only store small amounts of oxygen. Therefore, for very heavy, sustained exercise, new oxygen must be provided from outside the body if you expect to keep working.

In summary, the three different muscle metabolic systems that we have at our disposal to supply the various degrees of energy that are required for various activities are: (1) the **phosphagen system** (for 10-15 second "bursts" of energy), (2) the **glycogen-lactic acid system** (for another 30-40 seconds of energy), and (3) the **aerobic system** (providing a great deal of energy that is only limited by your body's ability to supply oxygen and other important nutrients). Many sports require the utilization of a combination of these metabolic systems. These systems are outlined in Table 1.

Table 1. The three different metabolic systems that we have at our disposal enable different degrees of muscle activation.

Muscle Metabolic Energy Systems	Duration of Maximal Muscle Activity	Activity Types
Phosphagen System	10-15 seconds	Power surges
Glycogen - Lactic acid system	30-40 seconds more	Intermediate athletic activities
Aerobic System	Unlimited time (as long as nutrients last)	Prolonged athletic activities

Not only do we have different metabolic systems to provide energy for our muscles but you have also learned that we have different "kinds" of muscle fibers, the **Type I (slow twitch) fibers** and the **Type II (fast twitch) fibers,**. These different muscle fiber types allow you to produce different kinds of movement. In a special activity that was designed for Student Investigation 3.3, you will be examining how your quadriceps muscles are able to support you in a certain position; this will enable you to determine how well you have been endowed with slow twitch fibers. In the meantime, however, let's finish this section by briefly discussing the topic of **animal experimentation**.

Animal Experimentation

In this chapter and the one that follows, you will be reviewing space flight investigations that were carried out using laboratory rats, including the muscle study that was designed by Dr. Kenneth Baldwin from the University of California at Irvine. We will be reviewing some of the objectives, methods, and results of his study in a moment. For now, though, it is important to discuss animal experimentation in general, because this is a topic that has touched each and every one of our lives. This section is not meant to end the debate on whether and how animals are used in research but, instead, it is meant to bring this topic out into the open so that debate can continue. You see, continued debate of this issue can serve as a way to ensure that we remain informed enough to judge for ourselves the necessity and merit of continuing this type of research. Our knowledge will also ensure that researchers who use animals **remain accountable** to their moral and scientific obligations to carry out only justifiable and humane animal studies.

Those who support animal experimentation claim that many of the cures for deadly diseases have been developed through experimentation on animals - and that is true. Those who oppose animal experimentation tell of terrible stories about how animals have been mistreated in some of the laboratories where they were used as experimental subjects - and this has happened in cases where researchers have behaved in inappropriate ways. The use of animals in science may not have always been as well-justified or well-executed as today's sensibilities require. Today, far fewer animals are used in research than are used for other purposes. An estimated 17 to 22 million vertebrate animals are used each year in research, education, and testing - less than 1% of the number killed for food. About 85 percent of these animals are rats and mice that have been bred for research. The other 15% include other small rodents, dogs, cats, rabbits, monkeys, and chimpanzees.

Scientists assume two major responsibilities when they study animals in research. The first is to ensure that the use of animals **contributes to the advancement of knowledge that will benefit other living things**. Not only are animals used to study diseases that afflict human beings but they are also used to improve veterinary treatments for other animals so that the quality of life of **all living things** can be improved. The second responsibility is to minimize any possible pain or distress that the animals may experience during the performance of an experiment. Whether you feel good, bad, or indifferent about the use of animals in the laboratory, we can all feel united by the fact that no one should ever cause an animal to suffer.

Why is there a need for animal experimentation? The reason for **any experiment** is to gain new knowledge that can be applied to the benefit of other living things. By studying animals, it is possible to obtain information that cannot be learned any other way. For instance, sometimes a scientist uses animals as **experimental models** to study human function; such models have biological similarities to humans that make them particularly useful for studying how to treat specific diseases. In these studies, many animals can be fed identical and closely monitored diets and can be housed under certain environmental conditions that can be totally controlled. In many cases, it is impossible to obtain the necessary number of human subjects that would be required to carry out a human study under such controlled situations and for such long periods of time. Sometimes a scientist requires the use of special techniques that require surgically entering the body to study some feature. When a new drug or surgical technique is developed, society deems it unethical to use that drug or technique first in human beings because of the possibility that it would cause harm rather than good. Many people question why these experimental procedures even have to be done at all.

Let's consider this question. A hundred years ago, good health was much more rare than it is today. In 1870, the leading cause of death in the United States was tuberculosis. Of all the people born in developed countries like the United States, a quarter were dead by the age of 25, and about half had died by the age of 50. Today, fully 97% of Americans live past their 25th birthday, and over 90 percent live to be older than 50. Better nutrition and sanitation did much to reduce the toll from infectious diseases. But these diseases could not have been eliminated as significant causes of death and illness without animal research. Today, animal research has contributed to the development of many important drugs, surgical techniques, and therapies that have helped us become a healthier population. For instance, animal research has resulted in the development of: chemotherapy approaches used in the treatment of cancer; drugs and techniques that greatly increase the chance for survival during organ transplant procedures; the drug lithium for the treatment of depression; a technique known as balloon angioplasty for the treatment of cardiovascular disease; vaccines against diphtheria, whooping cough, tetanus, and polio that we received as children; and antibiotics used to treat everything from minor infections to severe illnesses. Nearly half of the biomedical investigations carried out in the United States would not have been possible without laboratory animals.

Also, the same methods that have been developed to prevent and treat diseases in humans have improved the lives of countless animals. The animals that we keep as pets and raise for food would live shorter and less healthy lives were it not for animal research. Vaccines, antibiotics, anesthetics, surgical procedures, and other approaches developed in animals for human use are now commonly employed throughout veterinary medicine. Pets, livestock, and animals in zoos live longer, more comfortable, and healthier lives as a result of animal research. And in many cases, treatments have been developed specifically for animals. Vaccines for rabies, canine parvovirus, distemper, and feline leukemia virus have kept many animals from contracting these fatal diseases. In fact, treatments for heartworm infestation, a painful and ultimately fatal affliction in dogs, have been made possible through the use of research animals.

Animal research has also been integral to the preservation of many endangered species. The ability to eliminate parasitism, treat illnesses, use anesthetic devices, and promote breeding has improved the health and survival of many species. Through techniques like artificial insemination and embryo transfer, species that are endangered or have disappeared in the wild can now be managed or maintained. Research on the sexual behavior of animals has made it possible to breed many species in captivity, enabling endangered species to be reintroduced to the wild.

While it is often impossible to obtain full agreement by everyone about all of the issues related to animal experimentation, each person's opinion should always be respected. It is not difficult, however, to obtain everyone's full agreement with the principle that **the humane and kind treatment of animals should be of primary importance throughout the scientific community**. And it is not difficult to understand that animal research has taught us more about the world we live in and about the living things that inhabit that world. It is the responsibility of all of the life scientists throughout the world to perform their studies with the utmost respect for all living things. Everyone should insist that any experiment that involves the use of animals be carried out with careful and kind treatment of those animals.

In the next section, we will briefly discuss how your muscle types can change due to changing physical and environmental circumstances. This will lead us right into a discussion of how the absence of gravity can affect the types of muscles that astronauts maintain as well as the overall strength of these muscles. Remember that, in order to study the muscle, a scientist must be able to see the muscles directly. A proper muscle study requires more tissue than an astronaut should expect to donate, and so you should be aware that we will be discussing how animal tissues were used to study muscles in space.

SPACE PHYSIOLOGY

Muscles can change their character based on the kinds of stresses that they are exposed to. Most of you know this from personal experience. Normally, for day-to-day activities, your body movements take place within a certain personal comfort region. That means that you usually use the same muscle groups over and over in a repetitive habitual pattern. However, nearly everyone, at one time or another, has participated in sports or other physical activities that require muscle groups that have not been utilized in some time! Usually the next day, or at least by the second day afterward, you feel a soreness whenever you move; this soreness reminds you that you have moved out of your comfort region and into quite a different region! In order to move beyond our comfortable level of physical activity, we must activate muscle cells that we don't normally use heavily. That is, we change the pattern of usage of our muscles to fit the physical needs we are facing. In a similar way, we can stop using certain muscle groups frequently because we become ill or because our activity habits change. In this case, you've probably noticed that those muscles become weaker. In either case, we are actually changing the kinds of muscles that we have.

How can this happen? Well, muscles are constantly being built and rebuilt. In only 7 to 14 days, half of the protein in human muscle cells is broken down, discarded and replaced. It's as if you had a contractor constantly tearing down the rooms in your house and rebuilding them with new materials. After a month, you've got a brand new house. Next month you'll have another brand new one. If the number and strength of your muscle contractions change (that is, if you drastically change the level of activity that you are involved in), your muscles respond by changing their character.

The point is that the muscles **adapt** to new situations. It seems that essentially all body systems are capable of adapting in response to rapid changes in the environment. When we need our muscles, we can activate them almost immediately. When we don't need certain muscles, they can go into what could be called a "hibernation" mode. This hibernation mode, however, can cause the muscle fibers to actually change their type. Just think of someone you have known who has worn a cast on their leg for a while. When the cast is removed, the leg appears thinner and it is definitely weaker for a while until this person can rebuild his or her leg muscle strength. In this and other situations where a person does not use his or her muscles for a period of time, the muscles themselves begin to waste away, or **"atrophy."** For instance, people who are confined to bed during an illness or even astronauts who, while in space, do not require the use of their **"anti-gravity"** muscles both experience this natural atrophy. Such muscle atrophy can cause problems for people here on Earth and for astronauts who fly in space.

Muscle change can begin quickly. Dr. Baldwin and his colleagues carried out ground-based experiments with rats that are actually involved in activities that simulate liking weights. They are not standing up curling weights, obviously, but their feet push against an object. They participate in about two minutes of weight training a day and, within two days, changes in their muscle fiber types can be observed.

A group of Dr. Baldwin's rats also went up in space to determine just what happens to their muscles when gravity is removed. On their return, Dr. Baldwin discovered that being in micro gravity for 14 days had converted a large portion of their muscle fibers from Type I to TypeII. This is because, while in space, the rats no longer needed their legs to balance and control their bodies against the force of gravity. They floated around from one location to another (Figure 10). Therefore, their muscles actually began to change their character during space flight. Similarly, it is believed that astronaut's muscles weaken while in space because they do not have to use them as they normally would on Earth. When the astronauts return home, they experience gravity as much more of a force to reckon with than they had ever noticed before.

Figure 10. Gravity experiment with rats.

The space flight investigation that was developed by Dr. Baldwin and his research team was designed to carefully examine rat muscle changes that take place in space in order to try to understand how human muscles also change. In general, his experiment looked at the effects of space flight on:

- muscle mass and functional properties of skeletal muscles;
- running endurance capacity;
- the muscle cell's ability to use oxygen to convert nutrients into energy.

Just as in all of our other chapters, we should consider some general statements - or hypotheses - about what is expected from the results of Dr. Baldwin's experiment. Dr. Baldwin's original hypotheses, which served as the foundation for the development of his space flight study, are very complicated. We will discuss only a subset of his various measurement sets. For this reason, we will not be concerned with his original hypotheses, but will treat his experiment as if it involves only three "hypotheses":

Hypothesis 1
In microgravity, tension is reduced on muscles that support the body against gravity, resulting in a loss of muscle mass and an accompanying loss of muscle strength.

Hypothesis 2
Exposure to micro gravity will cause a reduction in the endurance capacity of skeletal muscle.

Hypothesis 3
The loss of endurance capacity will be due to a change in the muscle cell's ability to convert nutrients into energy.

Remember to keep these hypotheses in mind as we review some of the important measurement sets that were actually carried out during Dr. Baldwin's experiment in space. We will return to them at the conclusion of our examination of Dr. Baldwin's experiment.

Before we begin looking at Dr. Baldwin's space flight results, we will participate in a set of activities (Student Investigations) that were designed to help you understand more clearly how muscles work.

YOUR PERSPECTIVE

Before describing some of the actual experimental procedures that Dr. Baldwin and his team carried out, and before we present the results of those experiments, it is important for you to delve somewhat deeper into the muscle metabolism concepts that were presented earlier. In particular, you will actually be using your own muscles in various activities. This section presents three different but related Student Investigations that will help you understand how different kinds of physical activity utilize different muscle fiber types and energy systems within the body.

For the first Student Investigation, you will be asked to predict which sporting events utilize which muscle energy system. You can peek back at an earlier section of this chapter dealing with muscle energetic to find some extra hints to help you complete the exercise. The second Student Investigation expands on this knowledge of muscle energetic by involving each of you in the planning for a special "mini field day" for the class to participate in. You will be selecting a variety of different physical activities that will help you demonstrate various levels of strength, power, and endurance. Each activity will then be evaluated to determine which muscle energy system supplied the needed ALP to perform the activity.

The final Student Investigation is meant to refresh your memory regarding the difference between Type I and Type II muscle fibers. Again, you will actually participate in a physical activity. But this time, you are performing the activity in an attempt to evaluate if you have more Type I or Type II muscle fibers in your upper leg (quadriceps) muscles. It should be fun! Let's get started!

STUDENT INVESTIGATION 1

Predicting Which Muscle Energy Systems Are Used for Different Physical Activities

Background

In an earlier section in this chapter, it was stated that about 50% of our bodies is composed of muscles. Of course, this percentage will vary depending on how large our muscles are. In any case, **the muscles are the major energy-consuming components of our bodies**. What is so unique about muscle energy metabolism is that chemical energy (in the form of ATP) is transformed into mechanical energy (movement). Remember that there are three muscle energy systems that our bodies call on in order to perform various kinds of activities. Table 2 lists those systems, but we are going to review them briefly once again. After reviewing these systems, you will be asked to predict which of the energy systems are used in the performance of a selected list of sports activities. Let's first review the muscular energy systems and how they are used by the body.

Table 2. Muscle energy systems used for various magnitudes of activities.

Muscle Metabolic Energy Systems	Duration of Maximal Muscle Activity	Activity Types
Phosphagen System	10-15 seconds	Power surges
Glycogen - Lactic acid System	30-40 seconds more	Intermediate athletic activities
Aerobic System	Unlimited time (as long as nutrients last)	Prolonged athletic activities

The chemical energy that fuels our muscular activities is **adenosine triphosphate (ATP)**. For the first five or six seconds of muscle power, we can depend on the ATP that is already present in the muscle cells. Beyond this time, however, new amounts of ATP must be formed to enable the activation of muscular contractions needed to support longer and more vigorous physical activities. For activities that require a quick "burst" of energy that cannot be supplied by the ATP present in the muscle cells, the next 10-15 seconds of muscle power can be provided through our bodies use of the **phosphagen system**, which utilizes a substance called **creatine phosphate** to recycle ADP into ATP.

For longer and more intense periods of physical activity, however, our bodies must rely on systems that break down the sugars (glucose) in our bodies to produce ATP. The complete breakdown of glucose occurs in two ways: through **anaerobic respiration** (oxygen is not used), and through **aerobic respiration** (which occurs in the presence of oxygen).

The anaerobic utilization of glucose to form ATP occurs as our body increases its muscle use beyond the capability of the phosphagen system to supply energy. In particular, **the glycogen-lactic acid system**, through its anaerobic breakdown of glucose, provides about 30 - 40 seconds more of maximal muscle activity. For this system, each glucose molecule is split into two **pyruvic acid** molecules, and energy is released to form several ATP molecules providing the extra energy. The pyruvic acid will then partly break down further to produce **lactic acid**. If the lactic acid is allowed to accumulate in the muscle, you will experience muscle fatigue. At this point, the **aerobic system** must kick in.

The aerobic system in the body is utilized for those sports that require an extensive and enduring expenditure of energy such as a marathon race. That is, endurance sports absolutely require aerobic energy. Lots of ATP must be provided to your muscles in order to sustain the muscle power that you need to perform such events **without excessive production of lactic acid**. This can only be accomplished when oxygen in the body is used to break down the pyruvic acid (that was produced anaerobically) into carbon dioxide (C02), water, and energy by way of a very complex series of reactions known as the citric acid cycle. This cycle supports muscle utilization for as long as the nutrients in the body last. The breakdown of pyruvic acid requires oxygen, and slows or eliminates the accumulation of lactic acid.

In summary, the three different muscle metabolic systems that we have at our disposal to supply the energy required for various activities are: (1) the **phosphagen system** (for 10-15 second "bursts" of energy), (2) the **glycogen-lactic acid system** (for another 30-40 seconds of energy), and (3) the **aerobic system** (providing a great deal of energy that is only limited by your body's ability to supply oxygen and other important nutrients). Many sports require the utilization of a combination of these metabolic systems. By considering the **vigor** of a sports activity and its **duration**, one can estimate very closely which of the energy systems are used for each activity.

Now that we have reviewed the three different muscle metabolic systems, we are going to predict which systems are used to play certain sports. Let's get started.

Procedure
After reviewing the three muscle energy systems, predict which system is used to supply the muscular energy that is required to perform each sport listed in Table 3. Choose from the list of "Energy Systems" provided. There may be some hints in an earlier section of this chapter that dealt with "Muscle Energetics." Your teacher will provide you with a separate handout and each student will do this exercise independently. The entire class can discuss the answers together.

Table 3. Muscle energy systems used in various sporting events.

Various Sports	Enery System(s)
1. 50 meter dash	
2. 100 meter dash	
3. 400 meter dash	
4. 800 meter dash	
5. Marathon run (26.2 mi, 42.4 km)	
6. Jumping	
7. Basketball	
8. Tennis	
9. A single football play	
10. Cross-country skiing	
11. 1-mile run	
12. Ice-hockey plays	
13. 100 meter swim	
14. 400 meter swim	
15. A boxing match	
16. Jogging 5 miles	
17. Baseball home run	
18. Diving	
19. Weight lifting	
20. 10,000 meter skating	

Energy Systems

1. Phosphagen system, almost entirely
2. Phosphagen and glycogen-lactic acid systems
3. Glycogen-lactic acid system, mainly
4. Glycogen-lactic acid and aerobic systems
5. Aerobic system

STUDENT INVESTIGATION 2

Performing Physical Activities to Predict Energy Metabolism in the Expression of Strength, Power, and Endurance

Background

Our bodies are the **vehicles** that we drive to produce our physical movement. Of course, we as humans are much more than a moving machine, but for this activity we will be looking only at the physical aspects that provide for our mobility. We should always remember, however, that it is the intangible parts (the things we can't touch), more than the physical parts of ourselves that make us human. Nevertheless, for this section, let's describe our ability to move around in terms of this "vehicle" analogy. As you will see, this analogy does make some sense since the movement of a vehicle requires the interaction of many different parts, just like the body! After this Background section, you will be asked to design and carry out certain physical activities during a "mini field day" to demonstrate how various muscle energy systems contribute to the expression of muscle strength, power, and endurance. Of course, the strength, power, and endurance of a vehicle depend on its "make, model, and year," how well it is cared for, and what kind of fuel is used. All of this is true of our bodies as well!

Our "vehicles" come equipped with "standard equipment" including, in part, our cardiovascular system, pulmonary system, and muscles. The "computer" that controls the system lies primarily in our brain, and the "electrical system" that allows our computer to control the standard equipment and create movement is primarily the nerve conduction system. Our "navigational equipment" is composed of the various parts of our sensory and balance system (eyes, inner ear, muscular sensors, and touch sensors). And our vehicles can't do without the "fuel" provided by the utilization of the three different muscular energy systems.

In athletic events, our vehicles are expected to take us farther or faster than they do when we are performing normal day-to-day functions. Therefore, for athletic events, it is necessary to "change gears" to force our bodies to perform for us at a faster and more vigorous level. Changing gears often means changing the kind of muscle energy system that we must rely on to produce the muscle contractions that are appropriate for certain movements. We have already discussed under what circumstances our bodies utilize each of the three different muscle energy systems. Table X summarizes those systems. Changing gears also involves utilizing certain features within our bodies that, with extra effort, can even be "upgraded." These features are strength, power, and endurance.

Strength, power, and endurance are the special built-in features that we can find within our vehicles, or bodies, if we look for them. Each of these features can be expressed in a physical sense and an emotional sense. Let's talk about them only in terms of our skeletal muscles. The **strength** of a muscle is determined mainly by its size, with a maximum contractile force between 2.5 kg and 3.5 kg per cm of muscle cross-sectional area. That means that for every **cubic centimeter** of muscle mass that a person has, that person can create a force that is necessary to pull a 2.5 to 3.5 kg mass. That may not seem like much but if you look at your biceps muscle in your arm, you can see that it is composed of many cubic centimeters of muscle tissue (even if your muscles are small). So, **the bigger the muscle, the stronger the muscle** (Figure 11). As an example, a world-class weight lifter might have a quadriceps muscle (in the thigh) with a cross-sectional area as large as 150 cm . This would translate into a maximum contractile strength of 525 kg (1155 lb). Of course, on Earth, most of the tension would fall upon his patellar tendon in the knee, which could cause this tendon to be ruptured or actually torn from its insertion point below the knee. Yet, to make matters worse, the **holding strength** of muscles is about 40% greater than the **contractile strength**. That is, if a muscle is already contracted and a force then attempts to stretch out the muscle by increasing the time that the contraction must be held, this produces about 40% more force on the muscle. Therefore, the force of 525 kg calculated previously for the patellar tendon becomes 735 kg (1617 lb). This obviously further compounds the problems of the tendons, joints, and ligaments. It can also lead to internal tearing in the muscle itself.

The **power** of muscle contraction is different from muscle strength, because power is a measure of **the amount of work that the muscle can perform in a given period of time**. This is determined not only by the strength of the muscle contraction but also by its velocity of contraction (how fast it contracts) and the rate of contraction (the number of times that it contracts each minute). Muscle power is generally measured in kilogram-meters (kg-m) per minute. That is, a muscle that can lift a kilogram weight to a height of 1 meter or that can pull some object horizontally against a force of 1 kg for a distance of a meter in 1 minute is said to have a power of 1 kg-m/minute. The maximum power achievable by all the muscles in the body of a **highly trained athlete** with all the muscles working together is approximately the following:

First 10 to 15 seconds	7000 kg-m/min
Next 1 minute	4000 kg-m/min
Next 30 minutes	1700 kg-m/min

Thus, it is clear that a person has the capability for an extreme power surge for a short period of time, such as during a 100-meter race that can be completed entirely within the first 10 seconds. On the other hand, for long-term endurance events, the power output of the muscles is only one-fourth as great as during the initial power surge. Keep in mind that **this does not mean that one's athletic performance is four times as great** during the initial power surge as it is for the next half hour. The fact is that, during rapid bursts of activity, the muscle power output is less **efficient**. In contrast, for slower sustained activities, the efficiency for muscle power output is higher.

The final measure of muscle performance is **endurance**, or how long one can last while performing physical activities. This, to a great extent, depends on the nutritive support for the muscle. More than anything else, endurance depends on the amount of **glycogen** that has been stored in the muscle prior to the period of exercise. A person on a high carbohydrate diet stores far more glycogen in muscles than a person on either a mixed diet or a high fat diet. Therefore, endurance is greatly enhanced by a high carbohydrate diet. The corresponding amounts of glycogen stored in the muscle are approximately the following:

High carbohydrate diet	33 grams/kg of muscle
Mixed diet	17.5 grams/kg of muscle
High fat diet	6 grams/kg of muscle

To return to our "vehicle" analogy above, it is safe to say that a high carbohydrate diet is similar to "high octane fuel."

Now, why did we go into so much detail about the three characteristics of muscle capabilities? Well, you are going to design a set of activities that will demonstrate various combinations of physical strength, power, and endurance for the class to participate in. That is, your class will "test drive" each of your vehicles in various activities that you will define, and then you will get together to evaluate and rate the particular physical movements that were involved in each activity. So let's get started!

Procedure

Our main focus for this Student Investigation involves designing a mini field day that includes activities that demonstrate various levels of strength, power, and endurance. Each activity will be evaluated to determine which of the muscle energy systems is used in the body to perform such activities. The following steps will guide you in this exercise:

Step 1.

Each student will make a list of simple activities that could be done by the class during a "mini field day." These activities should require:

- different levels of strength, and
- different levels of power.

In addition, make sure to select activities in each category that vary in the **amount of endurance** that is required. You can use a copy of the chart in Table 4 to help you keep track of the different kinds of activities that you select. Keep your selections simple and reasonable and don't be afraid to be imaginative. The selections do not necessarily have to be normal track-and- field type activities. And your selections do not have to be competitive events. You can plan on activities for the whole class, or a few students can be selected to perform each one. Your teacher will inform you of the constraints (time, location) that the class must work within.

Step 2.

After each student makes an independent list of activities, discuss as a class the various options that were presented by the students and come up with a final list of activities that the class will participate in together. Once a list of activities is developed, design a chart (similar to Table 4, which will be provided by your teacher) to rate the activities in terms of the strength, power, and endurance needed to perform them. Try to select activities that represent different combinations of strength, power, and endurance. Then predict the kind of muscle energy systems each activity would probably utilize. These predictions will be your **hypotheses**. Use your experience with the previous exercise (Student Investigation 5.1) and Table 2 as a reference for this part of the discussion.

Step 3.
Now the fun begins! As the field day is held, evaluate the movements of each activity to see if your predictions were right. After performing the activities, the class will discuss which of the muscle energy systems were utilized for each activity by eval uating the physical movements that it took to perform each one. The field day is meant to offer the class an opportunity to understand how the different metabolic systems in the body contribute to a variety of physical movements. Enjoy yourselves!

Step 4.
As a final discussion point, look at each activity and evaluate how easy or how difficult it would be to perform them in the microgravity environment of space. How, then, might our body's energy systems change in space? Don't be afraid to use your imagination.

Table 4. Rate your list of activities based on their strength, power, and endurance characteristics. Predict which muscle energy systems will be used to perform the activities.

Endurance Ratings

Strength Ratings		LOW	MEDIUM	HIGH
	LOW	Activity		
		Power Level		
		Energy Systems Utilized		
	MEDIUM			
	HIGH			

STUDENT INVESTIGATION 3

Comparison of Type I Muscle Fiber Distribution in the Quadricep Muscle Groups

Background

Remember from a previous section that all muscles have varying percentages of **slow twitch (Type I)** and **fast twitch (Type II)** muscle fibers. Remember also that fast twitch fibers can deliver **extreme amounts of power for short periods of time**, while, on the other hand, slow twitch fibers provide endurance, **delivering prolonged strength of contraction over much longer periods of time**. For this exercise, you will be answering a few questions and performing a simple demonstration activity that, together, are designed to help you understand which muscle fiber type you may be particularly endowed with. Everyone is different. And a person who has more Type I muscle fibers cannot be considered "better" than a person who has more Type II fibers. This is simply an exercise for you to determine which fiber type is likely dominant in your upper leg muscle group, and to understand the different kinds of activities that you are usually involved in so that you can predict what muscle types dominate certain areas of your muscular make-up. Before we begin, let's go into a bit more detail about the difference between Type I and Type II muscle fibers.

Since we have reviewed the different energy systems that provide "fuel" to the muscles, you now have the background you need to explain **why** the two types of muscle fibers provide different kinds of movement capabilities. The following facts should clarify the differences for you:

1. Fast twitch fibers are about **two times as large in diameter** as slow twitch fibers.
2. The **enzymes** (chemicals that direct and accelerate chemical reactions in the body) that promote rapid release of energy from the phosphagen and glycogen-lactic acid energy systems are **two to three times as abundant** in fast twitch fibers as in slow twitch fibers, thus making the maximal power that can be achieved by fast twitch fibers as great as two times that of slow twitch fibers.

3. Slow twitch fibers are mainly organized for endurance, especially for generation of aerobic energy. They also contain considerably more **myoglobin** (a hemoglobin-like protein that combines with oxygen within the muscle fiber), and even more importantly, myoglobin increases the rate of diffusion of oxygen throughout the fiber by shuttling oxygen from one molecule of myoglobin to the next.
4. The **number of capillaries per mass of fibers is greater** in the vicinity of slow twitch fibers than in the vicinity of fast twitch fibers.
5. These facts indicate that:
    - **oxygen delivery and, therefore, the aerobic energy systems, dominate in the slow twitch fibers,** and
    - **the phosphagen and glycogen-lactic acid energy systems dominate in the fast twitch fibbers.**

This makes sense! But how do we know what kind of muscle fiber types we have in our own bodies?

Partly, it depends on the kinds of muscle fibers that you have either been endowed with through genetic expression (your parents would have a lot to do with that) or that you have developed due to the kinds of activities that you normally participate in. For instance, those of you who play basketball probably have a high percentage of Type I (slow twitch) fibers to allow for extended use of your muscles but also enough Type II (fast twitch) fibers to allow you to move quickly and powerfully to make the big score of the game. On the other hand, those of you who are sprinters in a track meet probably have a lower percentage of Type I (slow twitch) and more Type II fibers to allow for the quick bursts of power it takes to run fast over a short

No matter what kind of muscle fiber types you have, they all function by contracting, or shortening. Contractions that result in muscle fiber shortening are called **isotonic contractions** (iso = same; tonic = strength). An example of this is when you lift an object with your arm, your biceps muscles will shorten, allowing your arm to bend. In this case, you are matching and, in fact, increasing the force of your muscle contractions beyond the force exerted by the weight of the object, thereby lifting it. You may have experienced a situation, however, where you have tried to lift an object with your arm and you were not strong enough to lift it. Your biceps muscle could not produce enough force to match or overcome the pulling force of the object. In this case, your biceps were not able to contract and shorten the fibers in your muscles. This is called **isometric contractions** (iso = same; metric = length). For isometric contractions, the muscle fibers do not actually shorten, they are just **trying to** shorten. The simple activity that you will be asked to perform for this exercise is actually one that involves an isometric contraction.

With the knowledge of **how** the fiber types are different and **why** each of us develops different kinds of fiber types, let's begin our personal examination of what fiber types likely dominate our particular muscular makeup.

Materials
For this exercise, you will need only two things:

1. a stopwatch, and paper to record the results of the experiment.
2. paper to record the results of the experiment.

Procedure
You should break into small groups, or your teacher can select a handful of students to serve as "demonstration subjects" for this exercise. In either case, each student will perform the same activity. The activity was chosen to demonstrate the endurance capability of your quadricep muscles in your upper leg by performing an isometric contraction of the muscles for a period of time. The longer a student can hold the isometric contraction, the more likely that the student has a high percentage of Type I slow twitch fibers. If a student cannot hold the position for very long, it is more likely that this student has a higher percentage of Type II fast twitch fibers. Before the activity is started, think about what kinds of activities or sports each student is normally involved with and try to predict who would be more likely to withstand the activity the longest. These predictions will serve as the group's **hypotheses.**

This is how the activity should be carried out. Each student should stand with his/her back against a flat wall and, while the back is still touching the wall, each should slowly lower himself to a sitting position. At this point, the student's thighs should be parallel to the floor and the back should be flat against the wall. Now, start the stopwatch and time how long each can maintain the sitting position. Each student should try to hold the position as long as possible, but stop when you cannot tolerate the burning sensation is felt in the thighs. Once the student reaches a point where he/she cannot continue, have two students ready to pull the subject forward to relieve the isometric contraction. Repeat this exercise for each student.

Discussion
This demonstration will reveal some general characteristics about each student's upper leg muscles. The longer the student can hold his/her isometric contraction, the more likely he or she is to have a higher percentage of Type I muscle fibers. Here is the approximate breakdown related to the time each student is able to hold the position. If the student can hold the position for:

- less than 30 seconds, the student probably has more Type II muscle fibers in their upper leg;
- more than 30 seconds but less than 1 minute, the student probably has at least half of Type I muscle fibers in their upper leg (the closer the student comes to reaching one minute, the higher percentage of Type I fibers); and
- more than 1 minute indicates that the student's upper leg consists primarily of Type I muscle fibers

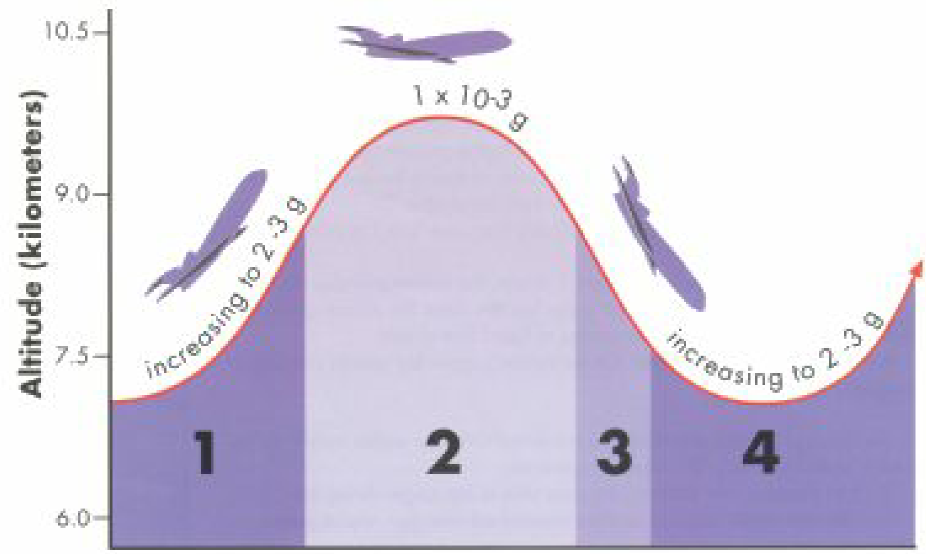
The results of this exercise should be compared with your earlier activity survey for each student to answer the following questions:

1. Does it appear that students who were able to last longer during this exercise also participate in sports or other physical activities that require greater endurance?
2. Does it appear that students who were not able to last very long during this exercise are those who normally participate in activities that require bursts of power?
3. Were your hypotheses supported or refuted by your data and observations?
4. Let's move on to review Dr. Baldwin's actual space flight experiment!

THE SPACE FLIGHT INVESTIGATION

The force of gravity on the Earth's surface has shaped the architecture of nearly all life. Our bodies look the way they do and function as they do partly because of the constant tug of this ever present gravitational force on all of our parts. We can only get away from gravity during brief moments in a very fast elevator or for an instant on an amusement park ride or when we venture into outer space. Another way to escape gravity that works for periods of up to about *30* seconds involves flying an up-and-down pattern in a jet airplane. Astronauts use this approach to develop and test equipment that will fly on the space shuttle and to verify that certain experimental techniques can actually be performed in the microgravity of space. A special airplane called the KC-135 is used to create these brief periods of microgravity by flying in a certain up-and- down pattern (called a **parabolic pattern**). Use of this airplane is important because it enables scientists to understand how to design experiments that will actually work in space. In fact, all of the space flight experiments that you have been or will be exposed to in this book have had some of their components tested on the KC-135 airplane; these even include the animal studies. In particular, for experiments using rats, it was necessary to actually take the rats for a ride on the KC-135 airplane to make sure that it was **safe** to work with them in microgravity, and that it was *feasible* to do the work planned without gravity. Let's see how gravity levels can change onboard the KC-135 airplane.

Figure 12.



During different portions of the KC-135 parabolic flight pattern, the force that are experienced by everything and everybody in the plane vary from almost a complete absence of gravity to about two to three times the force of gravity. These different forces alternate as the plane goes up and down. Figure 12 shows the parabolic flight pattern for the KC-135 airplane. The forces during flight can best be understood by breaking the flight pattern into its four main parts:

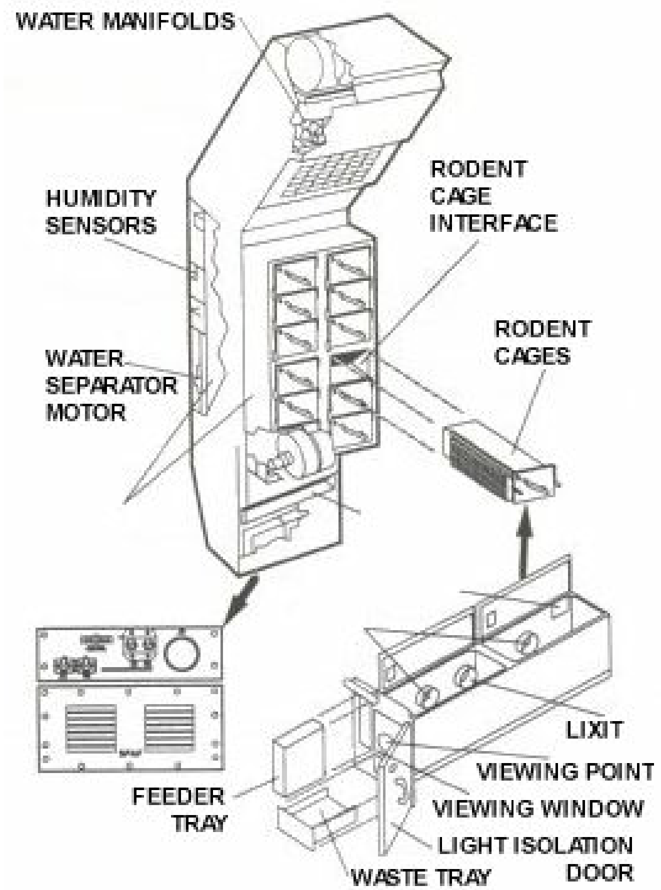
- In the first part, as the plane flies *upward,* the force that is exerted on everything in the plane grows to a level greater than the force of gravity because of the plane's **acceleration forces.** Many of you have experienced similar forces during "take off" in a plane.
- The second part is a transition period where the plane begins to arc, pulling out of the upward path and into the downward path. It is during this period that everything in the plane experiences about *30* seconds of **"free fall,"** similar to the briefer experience that one has when going over a hill in a

roller coaster. This period of free fall is the microgravity phase. During this phase, the force of gravity is effectively cancelled out by the forces produced by the plane's movement, and everyone in the plane begins to float (Figure 13).

- The third part, as the plane travels **downward**, is where gravity again begins to take control slowly.
- The fourth part is also a transition period where the plane again begins to arc, pulling out of the downward path and into the upward path. During this portion of the maneuver, forces are produced that are equivalent to about **two or three times the force of gravity!** If you can imagine how difficult it would be to lift your body if it weighed two or three times its current weight, then you can imagine how this portion of the flight must feel to the passengers of the plane. In fact, you may have experienced this on a roller coaster as it came to the bottom of a hill and quickly began another upward climb. As that scooping arc begins, your neck muscles can barely lift your head!

The KC-135 has served as a test facility for various pieces of research equipment and for different techniques employed for the study of rats in space. In particular, the **Research Animal Holding Facility (RAHF)** was flown onboard the KC-135 to ensure that it would operate correctly in microgravity. The RAHF contains 12 rodent cages, each of which can house two laboratory rats (Figure 14). The facility contains all food, water, environmental, and sanitation arrangements for each of its inhabitants and permits access to the animals during flight for health checks and if any other need arises. A monitoring system gathers feeding, activity, and environmental data.

Figure 14.



After the RAHF successfully operated in the KC135, it was certified for flight on the shuttle and plans were made to perform further tests of this equipment on an actual space flight mission. It was important to verify that the following subsystems of the RAHF functioned without any problems for longer periods in space:

- the environmental control system responsible for maintaining appropriate temperatures and humidity levels;
- the feeding and fluid delivery systems, which provide specially designed nutritional food bars for the rats to eat as well as a continuous water supply for the rats to drink **ad libitum** (at their will); and
- the ventilation system, which consists primarily of fans to circulate and filter the air within the RAHF as it moves from the space laboratory into the facility and back out again into the laboratory.

Proper operation of all three of these systems is obviously important for the health, safety, and wellbeing of the animals but one of these systems, in particular, is also important for the health and well-being of the astronauts as well. Can you guess which one?

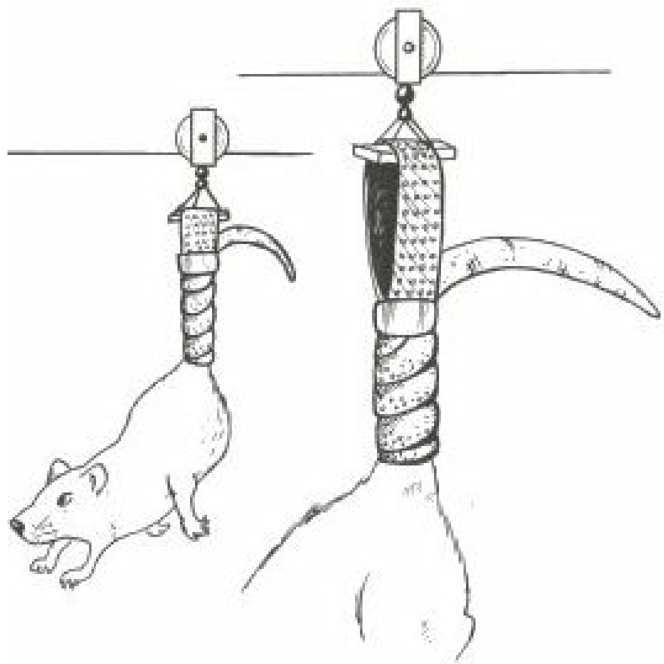
Most of the laboratory rats flown to accomplish Dr. Baldwin's experiment were accommodated in the RAHF. His experiment was actually carried out on different space missions that involved different amounts of inflight animal handling. For their first flight, the animals were handled very little and the actual experimental procedures and data collection were carried out on the animals only After they returned from space. On a subsequent mission, some of the experimental procedures on the rats **were** carried out in space and others were done upon their return. In either case, the techniques that were carried out and the data that was collected from the **flight animals** were matched by the techniques and data taken from **control animals.** The control animals were those rats that **did not get to fly in space** but that were housed in a similar RAHF here on Earth. These animals were exposed to the same environmental, dietary, and waste processing conditions as the flight animals were. Theoretically, then, the only difference between the experimental conditions of the flight and control animals was the presence or absence of gravity. The experimental data collected on the control animals served as a point of comparison for the data that were collected on the flight animals. This comparison served to **illuminate the effects of microgravity** on muscular function. In the next section, we will review the results of Dr. Baldwin's experiment.

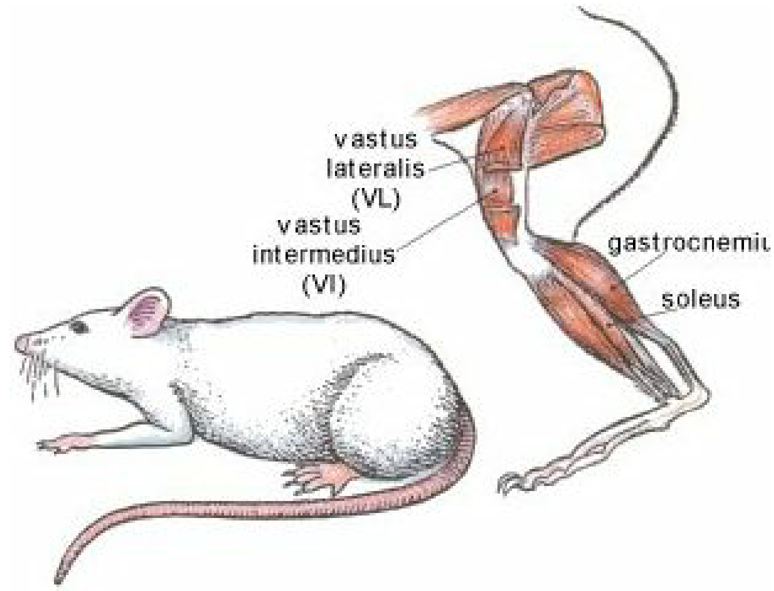
Dr. Baldwin's muscle experiment was designed to characterize the effects of microgravity on the structure and function of certain **anti-gravity muscles** in the **hind limb** of the rat. We will be looking at the results of only a subset of his various measurement sets, including:

- muscle mass and Type l/Type II muscle fiber distribution changes, and
- changes in the endurance level of rat muscle and a possible biochemical explanation for such changes.

So let's get started!

I. Measurements of Muscle Mass and Type I/Type II Muscle Fiber Distribution in the Rat Model





In muscle physiology research, whether on Earth or in space, the rat is often used as a **laboratory model** because rat muscles come very close to approximating the structure, function, and biochemistry of human muscle. (Isn't that a sobering thought?!!) In laboratories on Earth, studies have shown that both humans and rats lose muscle mass when they do not use their muscles. This loss of muscle mass has been measured in experiments where humans have been confined to bed for some period of time. To simulate similar **unloading** (taking all weight off of them) of the muscles in rats, researchers use a special **hind limb suspension** apparatus that lifts the back legs of the rat off the ground, rendering the animals incapable of using their legs to bear weight (Figure 15). Of course, in space, there is no need to put astronauts into bed or to suspend the hind limbs of the rats because everyone and everything *floats* in space, unloading the muscles naturally.

In microgravity, since astronauts and rats can float instead of walk, leg muscles become weakened from lack of use. Past space flight studies have shown decreases in muscle mass for both the astronauts and the rats. Specific changes include loss of lower body mass and decreased muscle strength. Dr. Baldwin's experiment was designed to **quantify** the decrease in the mass of the rat's hind limb muscles, muscles that are usually used to oppose gravity on Earth. This was done in order to develop a better understanding of how human muscles might be affected by microgravity. Figure 16 illustrates the particular hind limb muscles of the rat that Dr. Baldwin focused on.

Before we continue with our discussion of how Dr. Baldwin measured the mass changes in rats, let's discuss for a moment the concepts of **weight** and **mass.** Here on Earth, any one of us can "weigh" ourselves on a scale. The weight measurement that we obtain is an indication of **the gravitational attraction that the Earth has on the mass of our body**. Therefore, since the magnitude of the pull of gravity doesn't change, any change in "weight" is actually a reflection of a change in the "mass" of our bodies. Of course, the mass of our bodies refers to the "amount" of total stuff that our bodies are made of. All of this makes sense because, as we lose weight, the size or "amount of stuff" that our bodies are made of becomes smaller. The opposite is true when we gain weight. In space, where gravity is virtually absent, the only physical indication that we can obtain about our bodies is a measurement of our **nongravimetric** (non = without, gravi = refers to gravity, and metric = measure) **mass**.

In preparation for the Skylab missions that occurred in the early 1970s, efforts were undertaken to design equipment for the measurement of a variety of human physiological changes that were known to occur in space. One of the first priorities in space medical research was to determine the cause and time course of the weight loss which always seemed to accompany space flight. At that time, the main problem that had to be solved in order to carry out such a study was the lack of an instrument that could be used in space for nongravimetric mass measurement. How could they develop a mass - measurement device that did not depend on weight? The only alternative to the determination of gravitational attraction, or weight, was some determination of the **inertial property of mass.** Here are four statements that you should try to understand individually and then try to blend together in order to understand what is meant by "the inertial property of mass":

1. Inertia is **how *hard* it *is* to move a mass**;
2. Mass is a quantitative measure of inertia;
3. On Earth, weight and inertia are **proportional;** that is, the weight of an object here on Earth will directly affect how hard it is to move the object;
4. In space, there is no such thing as "weight" and, therefore, a determination of **how an object moves** is the key to measuring the mass of an object.

Figure 17

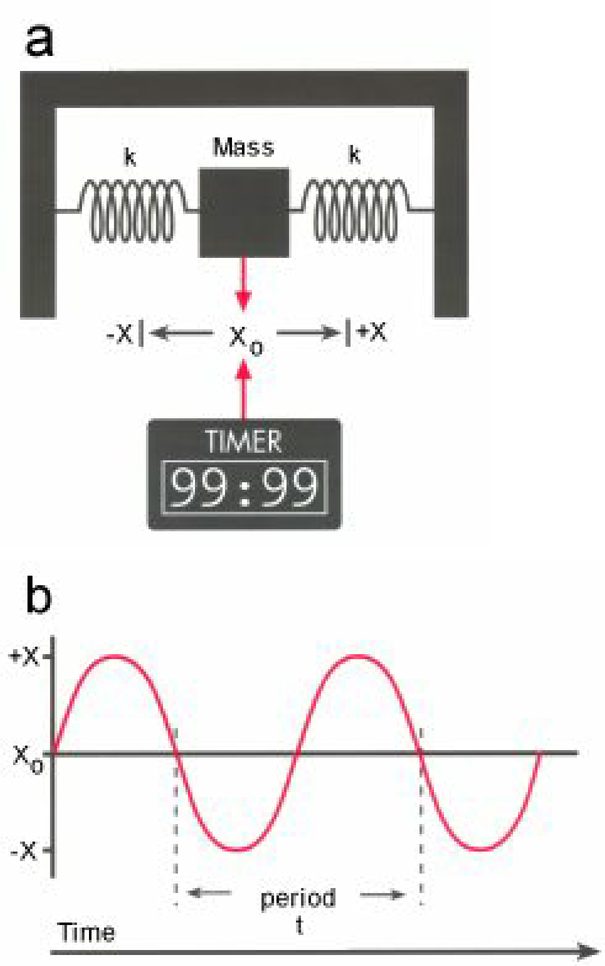


Figure 17 illustrates the principle of nongravimetric mass measurement. A sample mass (imagine this to be an astronaut in space) is placed between two springs and constrained to move from right to left **(linear motion)** along the longitudinal axes of the springs (Figure 17a). If the mass is displaced from its rest position (Xo) to a new position (X) and the mass assembly is released, it will undergo a round trip **undamped oscillation** (undamped = uninterrupted by other forces or friction, oscillation = back-and-forth motion) in a **period** (the time required to complete one round trip of the motion, see Figure 17b).

The physical relationship between the **period *of* oscillation** and **mass is** expressed in the following equation:

$$t = 2 p M / k$$, where

t = the **period of oscillation in seconds per round trip**,
M = the **mass** of the object in kilograms, and
K = the **spring constant** (which is a measure of the spring's "stiffness") in newtons per meter.
π = pi = 3.14159
If this **period of oscillation** is accurately measured by an appropriate timer, an object's mass may be calculated by rearranging the equation to obtain the following relationship:

$$M = K t / (2 \pi)$$

Figure 18 shows the current Body Mass Measurement Device (BMMD) that is used on the space shuttle. It allows the astronaut's mass to be measured based on the same principles that were developed and used in the Skylab program. After strapping the astronaut into the BMMD, the seat is unlocked and prepared by cocking the "displacement and release" device to allow the seat to begin oscillating. The timer is also turned on to enable a determination of the period of oscillation. As the astronaut takes a breath and holds it to avoid " jitter," the seat is released and begins to oscillate. The period of oscillation is recorded and a mass measurement is determined.

Figure 18. The Body Mass Measurement Device is used in space to measure the astronaut's mass every day to determine any changes that may result from space flight.

There is also a Small Mass Measuring Instrument (SMMI) that has been developed to determine inflight mass changes in small animals and other specimens. After all of this discussion about mass measurement in space, it is important for you to understand that, for very practical reasons, Dr. Baldwin **did not use** the SMMI to measure the muscle mass changes of rats. Rather than making inflight measurements, he waited until soon after the rats returned to Earth to begin handling the rats and determining their weights.

Rats are valuable models in muscle research, not only because their muscles are, in many ways, similar to human muscles, but also because rat muscles can be studied **directly.** That is, whole muscle groups can be **removed from the rat to** enable the researchers to study them more closely. Obviously, such a complete study is not possible with human muscles. Dr. Baldwin has performed muscle mass measurements by removing the muscles of rats that flew on a variety of missions. We will examine his results from both a nine-day mission and a six -day mission. Let's see how these measurements were carried out on these two missions.

Soon after the shuttle returned from nine days in space, the **flight rats** were unloaded from the RAHF, transported to a building near the shuttle landing site (where the **control rats** were located), and delivered to a waiting dissection team. Both the flight and control animals were weighed and then half of each group were immediately sacrificed by decapitation. The other half of the group were sacrificed nine days later (R+9) to see how rapidly the muscles regained their mass and strength. In either case, After sacrificing the animals, the muscles of interest were removed rapidly, along with other organs. The other organs were distributed to various scientists around the world who had other important investigations to carry out with these tissues. Then the muscles of interest were weighed. Of the particular muscle weights that are reported here, two come from the back of the thigh (Figure 16) and are known to be heavily involved in weight-bearing (antigravity) activities here on Earth. These include:

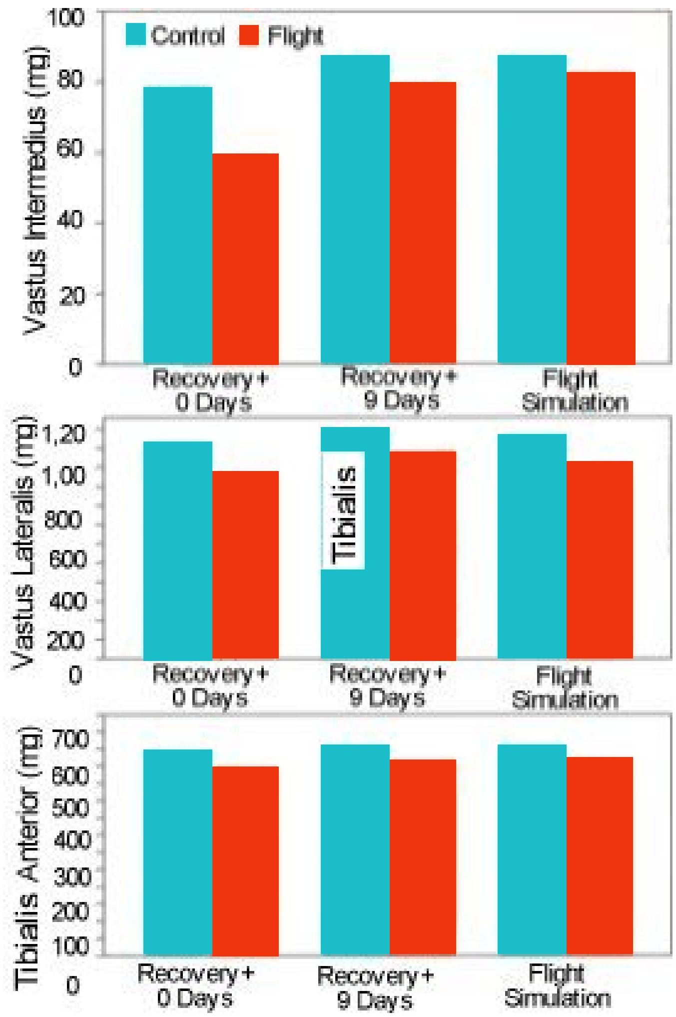
- the **predominantly *slow* twitch vastus intermedius (VI)** muscle, and
- the **predominantly fast twitch vastus lateralis (VL)** muscle.

The third muscle group that is reported on here is the **tibialis anterior** muscle, which is located in the ankle and is normally **not** heavily recruited in weight-bearing activity. The muscle weight results for each muscle group are shown in the graphs in Figure 19.

From the results in Figure 19, you can see that the total weights of the animals did not change very much. However, nine days of microgravity caused significant atrophy in both the fast twitch VL (15%) and slow twitch (22%). The slow-twitch VI experienced **more atrophy than the VL**, and interestingly, the tibialis anterior was **not affected** by microgravity. What does all of this mean?

First of all, since the body weights of the flight (FL) and control (CON) animals were not different, it is clear that the differences in muscle mass between FL and CON animals represent a **true atrophy response**. Secondly, these data indicate that the muscles that are primarily used as antigravity muscles on Earth (the slow twitch muscles) **change more** as a result of microgravity than the muscles that are used for bursts of activity (the fast twitch muscles). Third, while nine days of ground activity during the recovery period returned muscle mass back toward normal values, the recovery was incomplete, suggesting that a recovery period longer than the flight duration is needed to fully regain normal muscle mass, at least in the rat. Interestingly, the slow twitch Vl muscle, which is used more as an antigravity muscle, appeared to recover a greater portion of its mass than the VL After nine days back on Earth. This is consistent with the idea that weight-bearing is important in maintaining mass in the muscles that are composed chiefly of slow twitch muscle fibers.

Figure 19. Animal muscle weight comparisons between flight and control animals.



On a different space mission that lasted only six days, Dr. Baldwin examined changes in the rat's **soleus muscle**, a muscle that is located in the lower leg (Figure 16). This muscle **consists primarily of slow twitch, Type I muscle fibers** and is used extensively on Earth as an endurance muscle (similar to the vastus intermedius covered previously) to oppose the ever-present force of gravity. As you can see from Table 5, its muscle mass also decreased significantly as a result of space flight.

Table 5.	**Control**	**Flight**	**% Change**
Animal weight (g)	233 ± 7.8	216 ± 4.3	-7.3%
Soleus Muscle weight (mg)	102 ± 7.7	75 ± 7.2	-26.5%

Table 5. A comparison of animal and soleus muscle weight between flight and control animals.

Let's look at how the Type I and Type II muscle fibers in the soleus seemed to change their distribution.

Look at Table 6, which shows that there was a decrease in the cross - sectional area of Type I (by 24%) and Type II (by 2.7%) muscle fibers in the soleus muscle. But remember, there was a decrease overall in the mass of the muscle so it would be expected that since the **actual cross sectional area of the entire muscle would be decreased**, then the Type I and Type II cross-sectional areas would naturally be decreased. The real indicator that Type I fibers might have **actually been transformed** into Type II muscle fibers can be seen by looking at the changes in percent area for each fiber type. This is a different kind of comparison to make because, by looking at the **percent area** that the Type I and Type II muscle fibers occupy in the total muscle, you can directly compare the flight and control muscles without regard to their size differences. That is, it evens out the total size differences that exist between the soleus muscles of the rats that flew in space and the soleus muscles of the rats that served as ground controls. Let's use an example to illustrate the difference between **cross-sectional area** and **percent area.**

Table 6.	**Control**	**Flight**	**% Change**
Type I Cross-sectional area (mm^2)	2300 ± 276	1749 ± 362	-24.0%
Type II Cross-sectional area (mm^2)	2098 ± 262	2041 ± 244	-2.7%
Type I percent area (%)	71.2 ± 7.1	60.6 ± 5.9	-14.9%
Type II percent area (%)	28.8 ± 7.1	39.4 ± 5.9	+36.8%

Table 6. A comparison of the cross-sectional area and percent area differences in Type I and Type II muscle fiber for flight and control rat soleus muscles.

Consider the following cake analogy. Let's say that one of your parents has just made two cakes, a large square cake that measures 40 cm X 40 cm and a small square cake that measures 20 cm X 20 cm (Figure 20). Let's also say that you are starving and your parent will allow you to eat a quarter of either cake. Of course, your hunger will be more satisfied if you eat a quarter of the large cake because you will have a larger **cross-sectional area** of the cake to eat. Since the other cake is smaller, the **cross-sectional area** of a quarter of that cake will obviously be smaller. The **percent area** of each piece, however, would be the same - 25%. Thus, using the percent area of the two cakes will even out their size differences when making a comparison, **but not when making a decision on what cake to choose!** Now, let's get back to the results of Dr. Baldwin's experiment.

Table 6 indicates that the percent area that the Type I fibers occupied in the muscle decreased almost 15% between the flight animals and the control animals, but the percent area that the Type II fibers occupied in the muscle **increased almost 37%** between the two groups of animals! This suggests that some of the Type I fibers were transformed into Type II fibers because they were not utilized during space flight to the extent that they are used and needed here on Earth.

These studies have shown that not only does the elimination of weight- bearing activity cause a decrease in muscle mass, but it also causes a transformation of Type I into Type II muscle fibers in the predominantly slow twitch antigravity muscles in the rat model. Efforts are now underway to translate these data into an understanding of how human muscle is affected by reduced loading here on Earth (due to long illnesses that confine humans to bed) and by the microgravity environment of space. This work is important because such an understanding will allow **countermeasures** to be developed that reverse the detrimental effects of muscle atrophy. Let's take a look now at some of the results from Dr. Baldwin's study of how space flight influences the **endurance capacity** of rat muscles and let's see what he has found out about some of the biochemical explanations for these effects.

II. Changes in the Endurance Level of Rat Muscle and Possible Biochemical Explanation for Such Changes

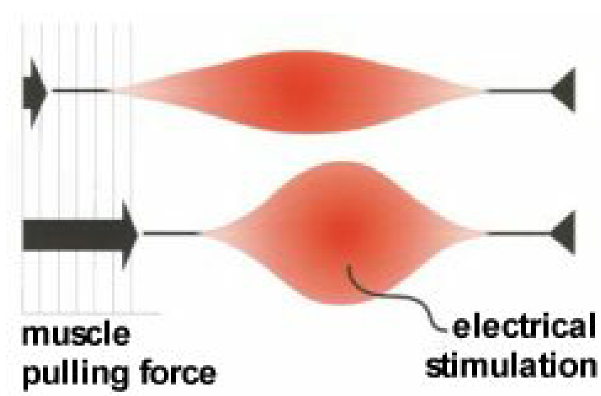
We have just seen that rat muscles lost mass, or **atrophied**, during space flight, particularly those muscles that are used extensively here on Earth to oppose the forces of gravity, i.e., the predominantly Type I antigravity muscles. We have also seen how Type I muscle fibers, used for endurance activities, seemed to transform themselves into Type II muscle fibers. This transformation probably occurs because of the animal's lack of need to stand up in space, but its different need to hop around using little bursts of activity to float from one side of the cage to the other. How do muscle atrophy and the Type l/Type II redistribution of muscle fibers affect the rat's overall endurance levels? You can probably guess the answer to that, but guesses aren't sufficient to answer questions scientifically. Dr. Baldwin carried out a study that examined how quickly the muscles of the rats that flew in space became fatigued and compared this result to the normal fatigue level for rats that did not fly in space. **Fatigue levels offer an indication of endurance capability in the muscle.**

In order to **measure** fatigue levels in the muscles of rats, it is not possible just to watch the rats exercise and try to figure out when they get tired. Not only are the rats not able to tell the researchers when their muscles have reached the point of fatigue, but the scientists require a technique that can provide a **quantitative** measurement to indicate to them **when** fatigue has occurred. Let's discuss the technique that Dr. Baldwin and his team used to measure fatigue levels. Remember, he performed this technique **postflight** on the rats that flew in space and on the control rats that remained on the ground.

The animals were anesthetized and, once unconscious, an incision was made in the skin of the left hind limb. The skin was separated from the animal's muscle groups in the leg and the **soleus muscle** was isolated. This means that the soleus muscle was identified and separated from the rest of the muscle groups while still remaining attached to the animal's leg. The hind limb of the animal was then placed into a device that provided rigid fixation of the hind limb so that it would remain stil l. The skin of the hind limb was pulled up, and the soleus muscle was bathed in a mineral oil so that the temperature of the muscle could be regulated (30 ŸC) and to prevent the muscle from drying out. Once the muscle was prepared in this manner, computers and other pieces of laboratory equipment were arranged so that they could be used to artificially stimulate the soleu s muscle to contract. A series of muscle contractions occurring over and over was used in order to produce fatigue in the muscle. After a certain point, the muscle is just not able to reach the level of **tension**, or tightness, that it coul d before it became fatigued. In order to induce these muscle contractions, the **sciatic nerve** in the leg was isolated and a wire electrode was placed around the nerve. The sciatic nerve is a **motor nerve** in the leg that ser ves as the pathway for signals that the brain sends for the muscles to contract and move. An electrical signal is passed through the electrodes, stimulating a sciatic nerve impulse (Figure 21). This **elect rical stimulation** of the sciatic nerve causes the muscle to contract.

The electrical signals were delivered to the nerve at a **frequency of 1 Hertz (1 Hz)** which is equal to one electrical signal per second. Each electrical pulse lasted 300 milliseconds (300 ms = 0.30 seconds). For this experiment, the muscle was stimulated to produce **isometric contractions** (where the muscle contracts but does not shorten) and the muscle tension level was measured.

Figure 21.



The duration of this **isometric fatigue test** was 2 minutes. Figure 22 shows Dr. Baldwin's results comparing the **percent of initial contraction** that was achieved over time. As you can see, the flight rats were much less able to maintain contraction levels than the control rats that had remained on Earth. In fact, at the end of the fatigue test, **the control group** produced 64% of the initial isometric tension whereas **the flight soleus muscles** were capable of only producing 36% of their initial isometric tension. Certainly space flight had taken its toll.

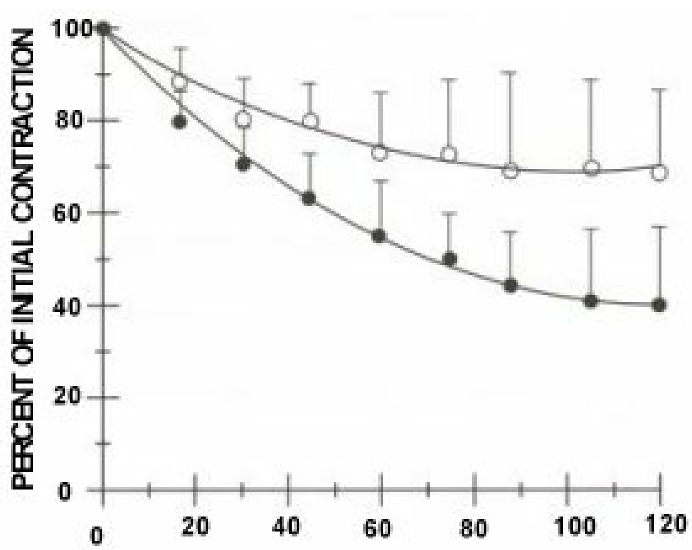


Figure 22.

We have just learned that space flight **does affect** the endurance level of rat muscles. The atrophied muscles are smaller and weaker and simply cannot perform as hard or as long as before. Prolonged and strong contraction of an atrophied muscle, then, leads more quickly to muscle fatigue. But it is not simply the size of the muscle that causes it to fatigue more rapidly. Studies performed on athletes here on Earth have shown that **muscle fatigue increases in almost direct proportion to the rate of depletion of muscle glycogen.**

Therefore, most fatigue probably results simply from our body's **inability to supply energy** to the muscle fibers for the muscle to perform its function. To explain the decrease in endurance levels for the rats that flew in space, Dr. Baldwin looked at some of the biochemical indicators of energy production in the muscles. Let's briefly discuss how the study of certain chemicals that come from the food we eat can help Dr. Baldwin understand how endurance levels are affected by space flight.

Metabolism includes all of the **chemical reactions** used by an organism to grow, feed, move, excrete waste products, and communicate. Metabolism has two major components: **anabolism**, or the synthesis (production) of biomolecules, and **catabolism**, or the oxidation (breakdown) of biomolecules for energy and the excretion of waste products. The manner in which any cell or organism, including humans, uses its **foodstuffs** (the stuff we eat) is organized into an orderly, very carefully regulated series of reaction steps and sequences known as **metabolic pathways**. Some of these metabolic pathways involve as many as a thousand different reactions before the final biological "event" takes place. For instance, a series of reactions occurs in the body after we eat certain foods. Foods are broken down into their basic chemical components and these chemicals continue to be **broken down**, or **oxidized**, and a chain of other chemicals are **produced**, or **synthesized**. Eventually, all of the reactions result in a final event. In our case, the biological event that we are talking about is **movement**, which is produced by our muscles.

We already know that ATP is the main ingredient that is necessary to fuel our muscle contractions, and, therefore, our movements. In order to produce ATP, our bodies must extract energy from the foods that we eat. As we digest our food, some of the chemicals from the food are broken into smaller chemicals (Figure 23). For instance:

- **carbohydrates** (including glycogen) from the fruits, vegetables, pastas, potatoes, grains and other things we eat are broken down into simple sugars (including glucose);
- **fats** from the ice cream, steaks, granola, chocolate and other things we eat are broken down into **fatty acids** and **glycerol**;
- **proteins** from the fish, peanut butter, eggs, milk, cheese, beans, and other things we eat are broken down into **amino acids**.

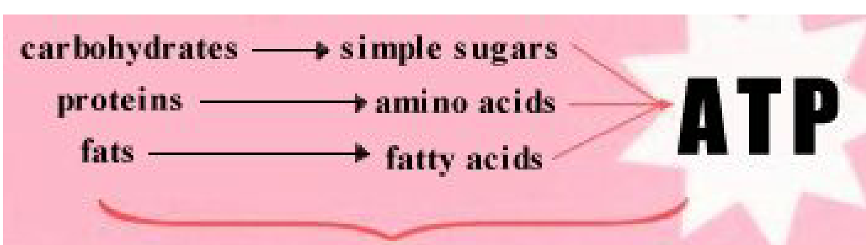


Figure 23. Energy sources in the body include carbohydrates, proteins, and fats, an of which eventually break down to help the body produce ATP.

ATP can be formed from any one of these compounds. We have previously focused on our bodies' ability to produce **glucose** in the various metabolic energy systems. This is appropriate since **our bodies prefer to use this carbohydrate pathway to produce ATP.** However, we must realize that fats are also used to produce ATP. In fact, fatty acids are the major **storage forms** of energy in the body.

Now, there are many, many steps that the carbohydrates and fats must go through to be put into a form that can help the body produce ATP. Someday you may study all of these steps in a biochemistry class, but for the purposes of understanding this part of Dr. Baldwin's experiment, just remember that carbohydrates and fats are the primary foodstuffs that our bodies use to produce ATP. They are oxidized (broken down) by the body, and this occurs at a certain characteristic **rate**, or speed.

Dr. Baldwin was interested in seeing if space flight might influence the proportion of energy that was produced by the carbohydrates and by the fats that we eat. In order to do that, he had to focus on a particular step in the breakdown reaction of each of these compounds. As mentioned previously, there can be up to a thousand reactions that chemicals go through to reach their final destination and final purpose. Dr. Baldwin focused on the **oxidation rate** (or breakdown) of two of the most important chemicals that are produced along the energy production pathways in our bodies: palmitate and pyruvate.

- **Pyruvate** is a chemical, or **substrate**, that is produced during the breakdown of **carbohydrates**.
- **Parmitate** is a chemical, or **substrate**, that is produced during the breakdown of **fats**.

By looking at the rate at which these two substrates are oxidized, Dr. Baldwin could determine which of these two pathways dominated the body's production of energy in space. The questions were whether the body used up its carbohydrates or fats in space at the same rates that it does on Earth. In other words, by measuring these two substrates, he would be able to tell whether the carbohydrate oxidative capacity, the fat oxidative capacity, or both of these energy producing pathways were affected by space flight.

There is one more issue to discuss related to oxidative capacity. Different kinds of muscle fibers, Type I (slow twitch) and Type II (fast twitch), have different oxidative capacities. We know that slow twitch muscles, which are used for endurance activities, **contain more blood vessels** to continually supply needed fuel for such activities. In fact, slow twitch fibers are often called **red muscle fibers**. This would suggest that they have a greater oxidative capacity than the fast twitch muscle fibers, which are sometimes called **white muscle fibers** because they **contain fewer blood vessels**. Therefore, because of their greater blood supply, the slow twitch muscles would have more oxygen available to oxidize substrates. It would be expected, then, that the slow twitch muscles should be able to oxidize both pyruvate and palmitate at a higher rate than fast twitch muscles, either on Earth or in space. Dr. Baldwin measured and compared the pyruvate and palmitate oxidative capacity of the **vastus intermedius (Vl) muscle**, the **red fibers of the vastus lateralis (RVL) muscle**, and the **white fibers of the vastus lateralis (WVL) muscle** for both the flight animals and the control animals.

Let's see what Dr. Baldwin found.

From Table 7, you can see two kinds of comparisons: (1) a comparison between the flight animals and the control animals, and (2) a comparison among the three different muscle fiber groups. First, you can see that **the capacity to oxidize pyruvate was not altered** between the flight and control groups of animals. As expected, however, there were some major differences in the capacity to oxidize pyruvate between the slow twitch (RVL) and fast twitch (WVL) muscles in both experimental groups. In contrast, **there were reductions in the capacity to oxidize palmitate** in all three muscle types of the flight group compared to the control group. These reductions amounted to:

Table 7. Pyruvate and palmitate oxidation in the vastus intermedius (VI) muscle, the red vastus lateralis (RVL) muscle, and the white vastus lateralis (WVL) muscle for both the flight and control rates.

Muscle Fiber Group	R+O Control	R+O Flight	R+9 Control	R+9 Flight
		Pyruvate		
VI	474 ± 31	468 ± 27	508 ± 27	485 ± 38
RVL	550 ± 29	493 ± 25	522 ± 25	458 ± 43
WVL	106 ± 9	105 ± 9	116 ± 5	122 ± 7
		Palmitate		
VI	73 ± 6	64 ± 5	75 ± 6	77 ± 6
RVL	58 ± 7	39 ± 6*	56 ± 4	51 ± 4
WVL	12 ± 1	8 ± 1*	10 ± 1	11 ± 2

- 12% VI muscle groups
- 38% red VL muscle fibers
- 36% white VL muscle fibers

Thus, overall, there was a reduction in fatty acid oxidation capacity for the rats that flew in space. Surprisingly, however, this effect was completely reversed by nine days after their return from space, even though normal muscle mass had not been completely restored (refer back to Figure 19).

These results provide some explanation for why the endurance levels of the rats that flew in space were reduced. The rats that flew in space seemed to develop a **greater dependence on using the carbohydrate pathway as an energy source**. This greater dependence on carbohydrates could possibly reduce the endurance capacity of the animal because the animal would use up its glycogen stores more rapidly. In addition, the flight rats **reduced their utilization of fats as an energy source**. Since fatty acids are the major storage forms of energy in the body, any reduction in the use of fats could also cause a reduction in the animal's endurance capacity. It is clear that these metabolic pathways (in particular, the oxidation of fats in our bodies) are affected by space flight.

CONTRATULATIONS!

We have just completed our examination of some of the important results of Dr. Baldwin's space flight investigation. These results, obtained from animal research, provide key information that should allow us to develop a better understanding of human muscle function in space and on Earth. In addition, these studies have provided some very strong hints about how to develop appropriate corrective procedures (**countermeasures**) of diet and exercise that would provide better health care for astronauts who fly in space and for patients here on Earth who are unable to maintain muscle integrity normally.

SPEAKING OF SPACE

One of the most important parts of being a scientist is being able to communicate the results of an experiment clearly to other scientists, to students, and to all of us, so that we can learn from it and so that we can help science move forward to new and better ideas and questions. Remember, **the knowledge that we obtain from scientific results is worthless unless we are able to communicate and share it with the rest of the world**. We are now going to participate in an activity designed to help us better understand how to present scientific results to those around us. You will be designing a presentation that will allow you to share, in your own words, the results of Dr. Baldwin's experiment.

The scientific results that you have just examined were described in two separate sections. To carry out this activity, your teacher will select two teams of students. Each team will take one of the two sections and develop a plan for presenting the information in a clear and concise way. In the development of this presentation, you should take into consideration the following points:

1. **Imagine that your small group is the actual scientific team that conceived of, planned, and carried out the experiment.** Introduce each member of the scientific team, indicating what his or her job was. Remember that, for this experiment, the only job that was carried out **inflight** was for the astronauts to perform health checks on the animals and to generally observe their behavior and activities. Most of the actual experimental work was done postflight.
2. **You should design your presentation as if your audience hasnever heard the information before.** This means that you must firstprovide enough background to your audience to understand the significance of the study. That is, you must explain why this study was important. Keep theaudience foremost in your mind as you design your presentation and alwaysmake it as easy as possible for your audience to understand**what** you are saying and **why** you are saying it.
3. **Explain the methods that were used to carry out the investigation, the results, and how the results either supported or refuted the hypotheses.** The description of your methods should include information about your **protocol** (steps carried out to complete the experiment), the **equipment** that was used and how it was used, information about who the **subjects** were and how many there were, and anything else that is relevant about your study. In planning for your presentation, you must also determine the best way to display your **results**. You may want to graph the data or present a table of values. If you choose to produce a graph, include a title, the units of measurement on each axis, a legend, and make it as clear as possible. Also, remember to tie the results of your study back to the relevant hypotheses:

Hypothesis 1

In microgravity, tension is reduced on muscles that support the body against gravity, resulting in a loss of muscle mass and an accompanying loss of muscle strength.

Hypothesis 2

Exposure to microgravity will cause a reduction in the endurance capacity of skeletal muscle.

Hypothesis 3

The loss of endurance capacity will be due to a change in the muscle cell's ability to convert nutrients into energy.

4. **Explain what the results indicate about how the body responds to space flight.** Also try to determine how the results might affect our understanding of human physiology here on Earth. Which, if any, health problems that we encounter he re on Earth might be helped by the knowledge you have gained from your space flight results?

Keep in mind that there are literally dozens (and sometimes hundreds) of people involved in carrying out a space flight investigation, each of whom is responsible for his or her very own specific aspect of the study, and each of whom is absolutely necessary to the success of both the individual experiment and the overall mission. There should be plenty of different roles for the different members of your team. There should certainly be a Principal Investigator who is in charge of the whole study, just as Dr. Baldwin was in charge of the real study that we've been learning about in this chapter. Also, a member of your team might serve as the engineer involved with the equipment. Another member of your team might be a physician or a physiologist assigned to make sure all of the experimental procedures are carried out safely. This is particularly important because the safety of the astronaut is always the first consideration. The team might also include various technicians responsible for collecting the data or producing the graphics. You may want to use more than one person to present the experiment to your audience. And don't be afraid to use plenty of visual aids. Be imaginative, but also be faithful to the main objectives of your experiment.

After each presentation, there should be a short question and answer (Q&A) period so that the audience has the chance to ask relevant, thoughtful questions. Rely on your team members to help you answer the questions. Don't let this Q&A session scare you. It is always a part of any well planned presentation. And remember, you will be on the other side of the fence asking questions of all the other groups!

Good Luck!

Conclusion

Well, we have finished. It can safely be said that **you possess more knowledge about what happens to muscles in space than almost everyone else in the world!**

REVIEW QUESTIONS

Earth Physiology

1. Sketch and Identity three Kinds of muscles in our bodies and give an example of each.

2. Briefly describe the five sequences of "electrical neuromuscular events" that regulate the heart's pumping action.

3. What muscle is used by the body to move food through the digestive tract and how is it structured to do this?

4.
   A. Frowning, smiling, closing the eyelids and raising one's eyebrows are made possible through the use of what kind of muscle?
   B. Dancing, walking, and standing are made possible through the use of what kind of muscle?
   C. What is the primary difference between the muscles in A and in B?

5. Identify the two types of muscle fibers and identify which type might be found in three different kinds of athletes.

6. Describe the structure in the muscle that is referred to as the "engine of the muscle."

7.
   A. Identify the basic source of chemical energy for muscle contraction and write its chemical formula.
   B. Explain how energy is extracted from this chemical source.

8. List the three muscle energy systems that are used for various sporting activities and name two activities that each system could support.

Space Physiology

1. What happens to muscles in space and why is this so?

2. Select one of Dr. Baldwin's hypotheses and, using any of the data sets in this chapter, provide an argument that supports or refutes the hypothesis.

3. Describe isotonic contractions and isometric contractions and the difference between the two.

4.
   A. Name the airplane that is used for microgravity simulation flights.
   B. Sketch and describe the flight pattern that it flies and identify what occurs during the different stages of the flight pattern.

5. The measurement of what muscle characteristic will provide an indication of the fatigue level in a muscle? Describe how such a measurement would be performed.

6. Draw an analogy that describes the transmission of a nerve impulse. Describe the similarities and differences between the analog and an actual impulse transmission.

7. Explain the terms anabolism and catabolism and their relationship to metabolism.

Critical Thinking

1. Define nongravimetric mass and describe the process of mass measurement in space.

References

Certain parts of the text were excerpted and adapted from the following publications and other references:

For the section describing Earth Physiology:

1. Astrand P-O, Rodahl K (1986). **Textbook of Work Physiology: Physiological Bassis of Exercise**, 3rd ed. McGraw-Hill Book Company, New York.
2. Brown WH, McClarin JA (1980). **Introduction to Organic and Biochemistry**, 3rd ed. Willard Grant Press, Boston, Massachusetts.
3. Fox Sl (1987). **Human Physiology**, 2nd ed. William C Brown Publishers, Dubuque, Iowa.
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5. Nourse AE (1964). **The Body**. Life Science Laboratory, Time Incorporated, New York.
6. Oram RF (1989). **Biology: Living Systems**. Merrill Publishing Company, Columbus, OH.
7. **Equine Exercise Physiology** (1983). Snow DH, Persson soft Rose RJ (eds.), Burlington Press: Granta Editions.
8. **The Incredible Machine** (1992). Poole RM (ad.), National Geographic Society, Washington, DC.

For the section describing Earth physiology, particularly the examples pointed out related to muscle structure and the comparison between Michael Jordan and Mother Teresa:

1. Emmons S (1994). Miracle muscles. **Los Angeles Times**, January 30, 1994.

For the section discussing animal experimentation:

1. **Science, Medicine, and Animals** (1991). Report by the Committee on the Use of Animals in Research, National Academy of Sciences. National Academy Press, Washington, DC.

For the section describing the space flight results and as influence for numerous figures and tables:

1. Baldwin KM, Herrick RE, McCue SA (1993). Substrate oxidation capacity in rodent skeletal muscle: effects of exposure to zero gravity. **J. Appl. Physiol.** 75(6): 2466-2470.
2. Caiozzo VJ, Baker MJ, Herrick RE, Tao M, Baldwin KM (1994). Effect of spaceflight on skeletal muscle: mechanical properties and myosin isoform content of a slow antigravity muscle. **J. Appl. Physiol.** In press.
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5. **Biomedical Results from Skylab** (1977). Johnston S. Dietlein LF (eds.), SP-377, NASA Headquarters, Washington, DC.
6. **Spacelab life Sciences 1: 180-day Preliminary Results** (1991). NASA Headquarters, Washingtan, DC.

Figure 3. Cardiac muscle cells (fibers) are capable of contracting spontaneously; that is, without a nerve stimulus. A network of specialized muscle fibers, which conduct electrophysiological impulses, works to establish a unified contraction across the e ntire heart muscle. If all the individual cardiac muscle cells contracted independently without synchrony, no effective pumping action would occur.

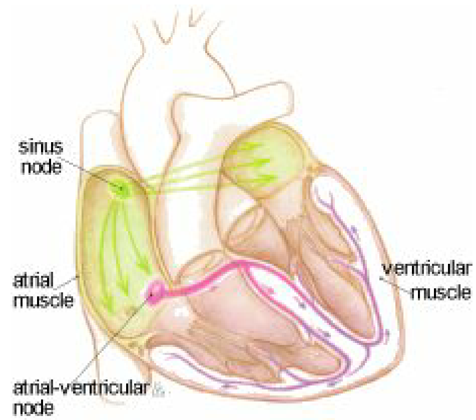


Figure 4. The alternating contractions of circular and longitudinal smooth muscle layers produce peristaltic waves, which propel the contents of these tubes in one direction.

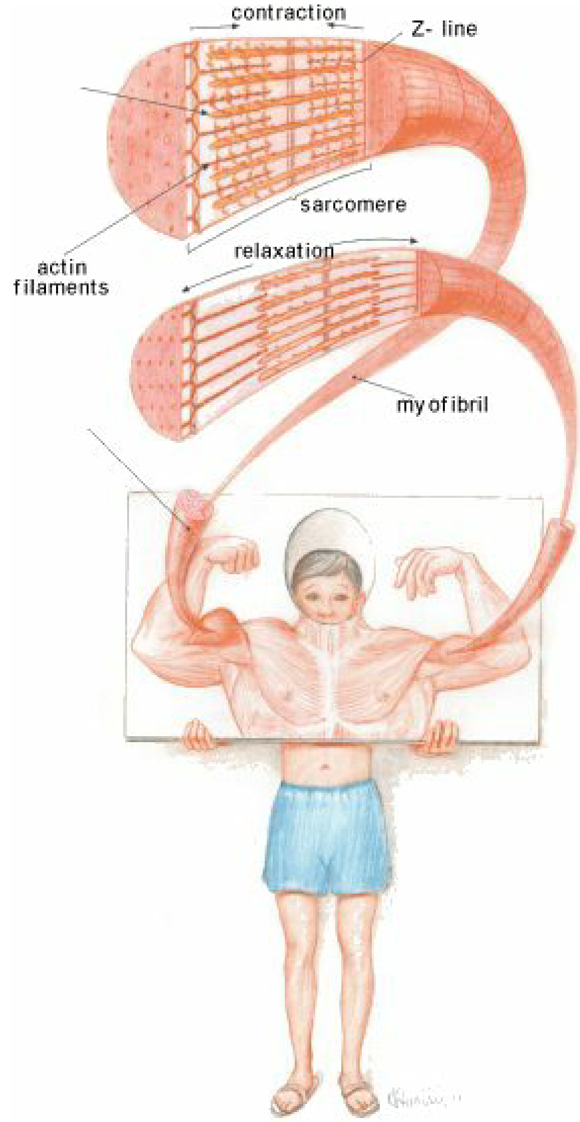


Figure 6. The sarcomere of a contracted muscle fiber shortens as the myosin and actin filament slide together to overlap, resulting in thicker, stronger muscle myofibrils and muscle fibers.

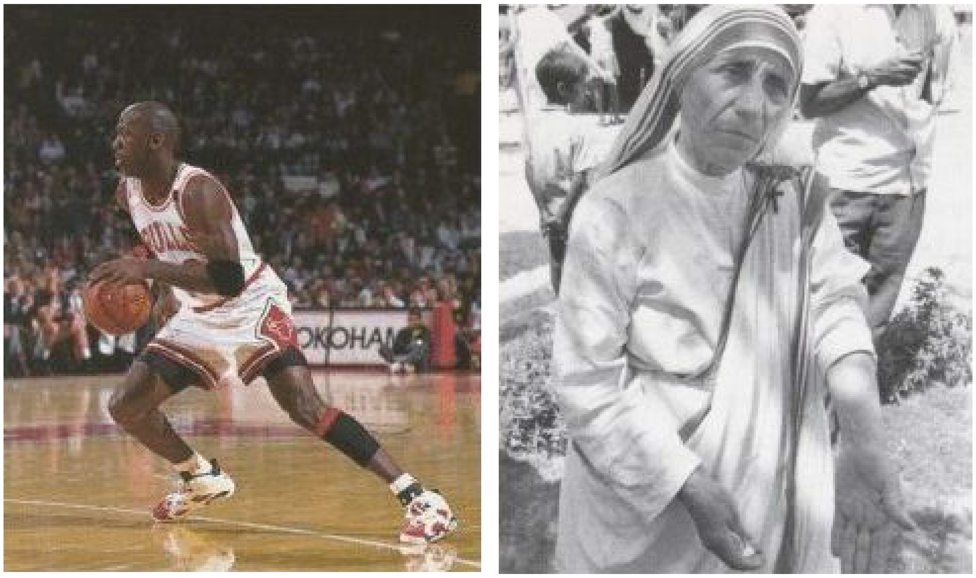
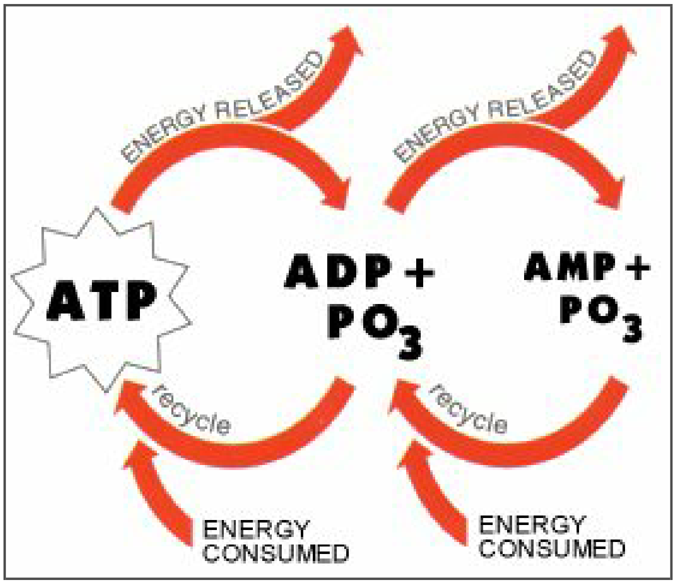


Figure 7. Believe it or not, equivalent types of muscle filaments in Michael Jordan and Mother Teresa are identical In fact, your muscle filaments are identical to Michael Jordan's and Mother Teresa's also! Of course, Michael Jordan's muscle fibers contain more filaments, resulting in much larger muscles.

Figure 8. Adenosine triphosphate (ATP) is the basic source of chemical energy for muscle contraction. Energy is provided as ATP is broken down into ADP, and then again into AMP. Less energy is required to recycle the chemicals back into ATP.



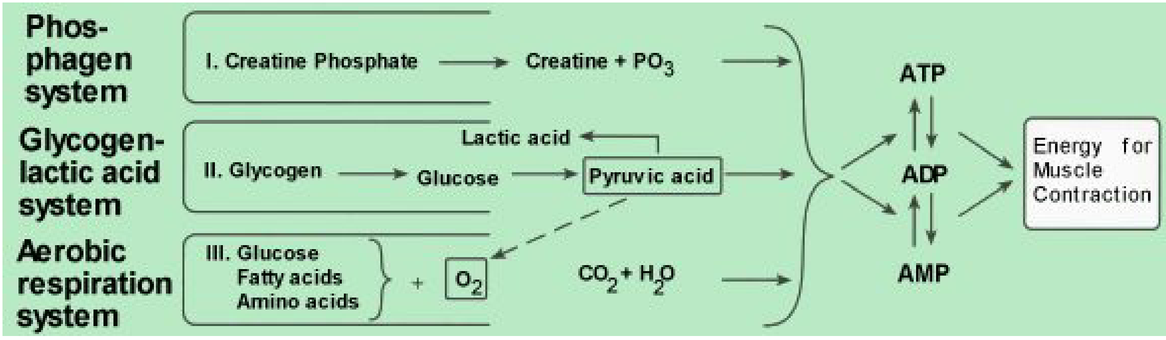


Figure 9. The three important metabolic systems that supply energy for muscle contraction: (1) The phosphagen energy system, (2) the glycogen-lactic acid system, and (3) the aerobic system.

Figure 10. Laboratory rats that flew in space floated around in their cages and did not utilize their anti-gravity muscles in the same way they would on Earth.

Figure 11. Weight lifting will help develop larger muscles. The larger they are, the stronger they are.

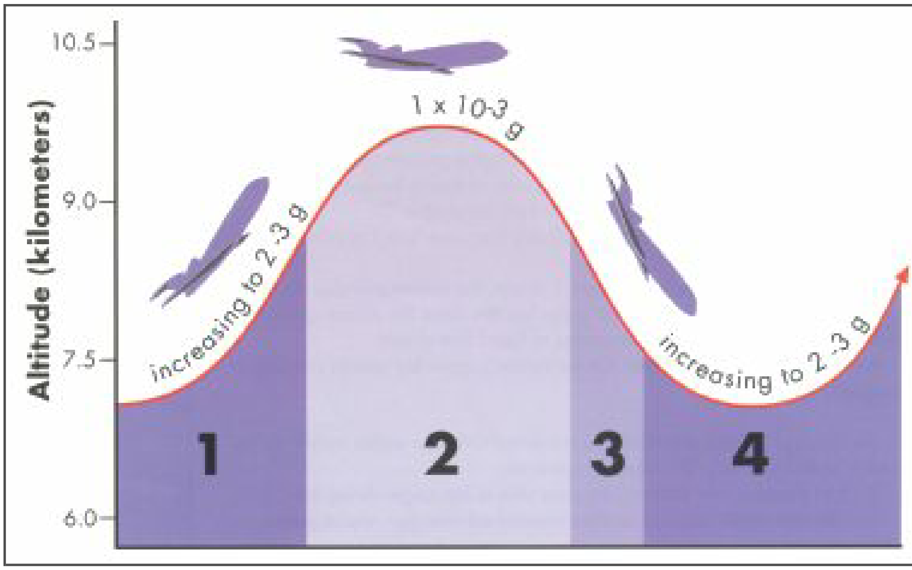
Figure 12. The forces that are produced during a KC- 135 airplane flight are broken into four parts: (1) acceleration forces during the upward phase of flight produce a growing level of forces on the plane and its inhabitants, (2) the transition phase from an upward direction to a downward direction produces "free fall" conditions, (3) the downward phase of flight produces slowly increasing forces on the plane and its passengers, and (4) the transition phase from a downward direction to an upward direction creates forces that are two to three times greater than the force of gravity.	

Figure 13. One way to escape the clutches of gravity for a short period of time is to fly in the KC-135 parabolic airplane. Both humans and animals find the floating experience to be very strange! In fact, because of the disorientation that occurs duri ng the floating experience, many people become very sick, which has led to a nickname for the flight - the vomit comet! The patch that is given to individuals who have flown on the aircraft depicts very accurately the possible ill effects of flying on th e KC-135.

Figure 14. The Research Animal Holding Facility (RAHF) was designed to house laboratory animals that fly in the space shuttle.

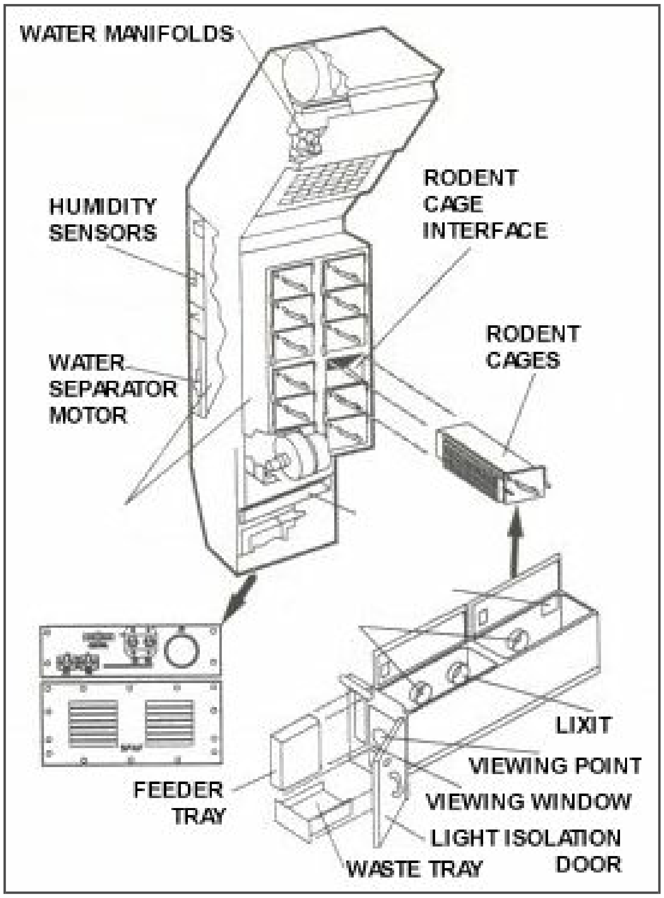


Figure 15. To study the effects of muscle "unloading" on Earth, researchers employ the use of the rat hind limb suspension technique. The technique is not painful and the special pully system allows the rat to move around using his front legs.

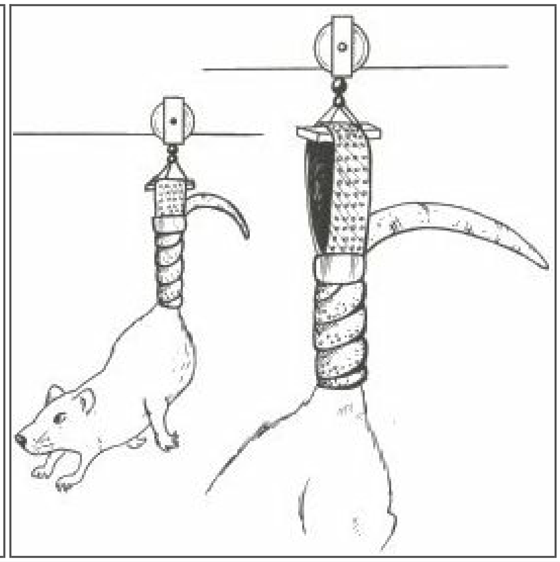
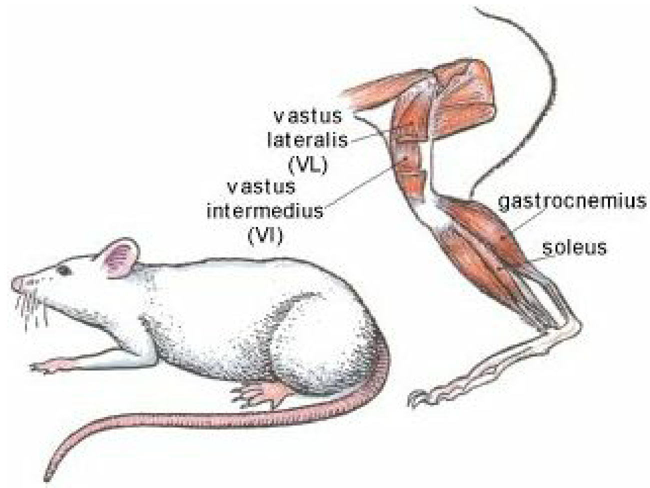


Figure 16. **Part of Dr. Baldwin's experiment involved measuring the mass of the rat's hind limb muscles including the gastrocnemius, the vastus lateralis, and the vastus intermedius muscle groups.**



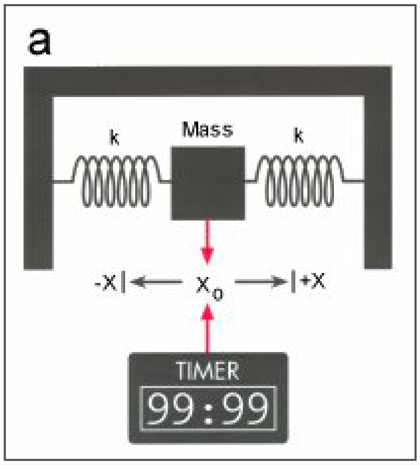


Figure 17. (a) A schematic representation of a simple spring/mass oscillator moving in a horizontal direction with no gravitational effects.

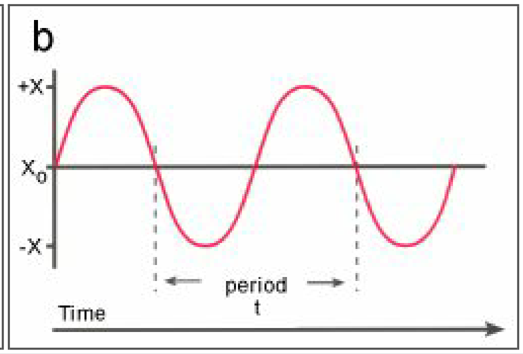
(b)A representation of its oscillating displacement distance over time.	

Figure 20. Each piece of cake represents 25% of a full cake. However, the two peices have very different cross-sectional areas. Recall that area=length x width.

Figure 21. A schematic representation of the electrical stimulation of a motor nerve to produce a muscle contraction.

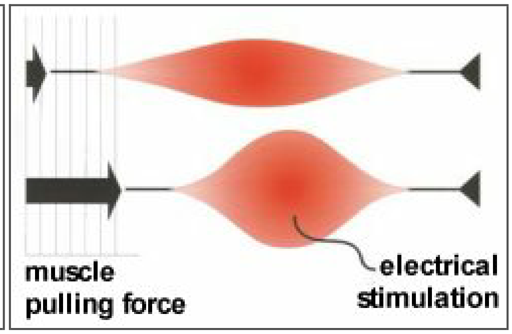


Figure 22. Isometric fatigue data of control (open circles) and flight (closed circles) soleus muscles. Note that the flight muscles were more fatigable than the control muscles. Values are means + standard deviation.